A MODEL STUDY OF MECHANICAL AERATION AS RELATED TO AGRICULTURAL WASTE DISPOSAL SYSTEM APPLICATION

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PREFACE

It is difficult for me to find the words to properly express my feeling of gratitude and appreciation to Dr. Gordon L. Nelson, my major adviser. He has always been a source of knowledge; one who has somehow always found time to be of assistance when needed; and an inspiration through his example and professional stature.

Prof. Quintin B. Graves' assistance and suggestions are gratefully acknowledged. The atmosphere created by the joint efforts of Prof. Graves and Dr. Nelson resulted in what can be described as an interdisciplinary effort for the departments of agricultural engineering and civil engineering.

The assistance and suggestions of the remaining members of the advisory committee, Associate Professor Elmer Daniel and Professor E. W. Schroeder are appreciated.

Dr. Lawrence O. Roth provided photographic assistance and Jack Fryrear provided the necessary assistance for drafting needs in the preparation of Figures and drawings.

The computer facilities of both Oklahoma State University and the University of Connecticut were used for this study. At the latter institution, part of the support for this activity came from grant GP-1819 of the National Science Foundation. In the initial computer work at Oklahoma State University, an IBM 1410 program originally developed by W. R. Gwinn of the USDA ARS SWCRD located at Stillwater was modified for this purpose and used. As the thesis data analysis progressed, this

program was replaced by programs developed by the author.

Last, but not least, are the technicians in agricultural engineering and the research development laboratory who constructed the apparatus for laboratory experimentation.

The study itself would not have been possible were it not for receipt of a National Science Foundation Faculty Fellowship. There were also a number of sacrifices required of my wife and family during this period before the overall objective could be achieved.

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CHAPTER I

INTRODUCTION

Large scale animal or fowl operations, when combined with confined housing practices, have created a serious problem in the handling and disposal of animal waste excretions. In the Southwestern states, the problem is one of waste accumulation and management resulting from the concentration of cattle feeding in large feedlots with animal capacities measured in the thousands (27). With poultry, the concern has been such that the first national symposium on poultry industry waste management was held at the University of Nebraska in May of 1963. This was followed by a second symposium on the same subject in 1964. With swine operations, it has been estimated that the future marketing capability of one confinement unit will be 1,000 to 100,000 hogs per year (35).

In addition, the above becomes increasingly important when it is related to the farm operation that is located near an urban center of population. For example, the state of California is already faced with such a problem for large scale cage type poultry operations (14). In other areas of the country, such as the Northeastern United States, this problem is currently beginning to present itself.

The use of free stall dairy housing systems has changed the dairy manure handling concept to one of "liquid manure" or "slurry". This is due to the fact that bedding usage is minimized as compared to the conventional or loose housing practices. With free stalls, a grid type floor over a semi-continuous or continuous collection pit could be used to collect the feces and urine excreted from the animals. If this practice were to be followed, then there is a potential for consideration of the use of the oxidation ditch system described by Okun in his discussion of wastewater treatment in Europe (28). The application cited was for small communities, but the agricultural animal size enterprise can be looked upon as being somewhat the equivalent of such installations. Animal wastes under these circumstances may be the equivalent of a large city from a strength standpoint although from a volume point of view the waste quantity being handled may be smaller.

Related to the conditions already described, the USDA Agricultural Research Service Farm Equipment and Structures Research Advisory Committee in its report of January, 1963 made the following statements and recommendation.

> There is evidence that some current methods of temporary storage contribute to sanitation problems affecting the health of the animals or poultry and certain methods of disposal lead to contamination of domestic water supplies. Flies, dust, and odors are part of this problem.
>
> Therefore, it is recommended that the current limited research in this area be expanded at once to determine the location and magnitude of the problems, analyze the shortcomings of current practices, and to develop criteria for solving the problems.

Problem Statement

Although there are a number of references on the subject of sanitary engineering the ones needed for the solution of agricultural problems are inadequate. In terms of establishing basic design criteria for the sanitary engineering of agricultural wastes, a useful tool, if feasible, would be the application of the theory of similitude in conjunction with the use of models. This tool, generally speaking, has been of value in the early development stage of solution to many problems in the past. It requires that the design requirements for the model be ascertained along with the establishment of what the model operating requirements should be.

With the current interest in the housing of cattle on grid floors, a method of collecting and handling feces and urine which contribute to a reduction in volume is desirable. One possible treatment process for this purpose is mechanical aeration. This method makes use of mechanical devices such as paddle or spray mechanisms, or aspirating devices to introduce oxygen into a slurry (34).

Babbitt and Baumann (5) cite the relative simplicity of mechanical equipment for slurry agitation purposes. Relating this to agricultural application, this would be a desirable feature to have with the waste treatment process used. The second factor of importance is economics. Kappe (18), in a resume of operating experience with mechanical surface aeration, concludes that this approach has made it possible for small towns to provide complete treatment at a low first cost and reasonable operation cost. As for installation size limitation, Roe (32) indicates that such systems are uneconomical if the operating capacity is greater than approximately 1 million gallons per day. The size of agricultural installations for consideration are on a much smaller scale.

Objectives

The objectives of the study were:

1. To establish a method whereby model studies can be used to

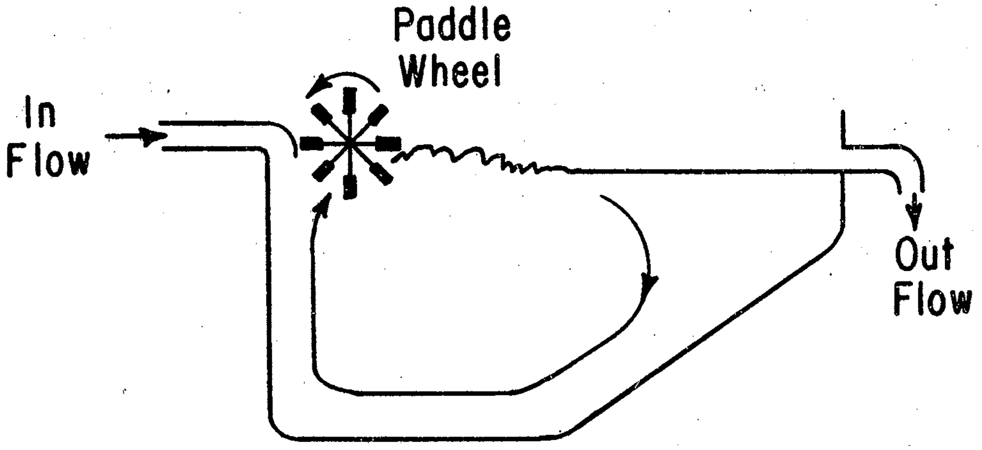
evaluate the efficiency of mechanical aerators for agricultural waste disposal systems.

2. To develop a prediction equation for describing the effectiveness of a rotor paddle aerator for transferring oxygen from air to a liquid.

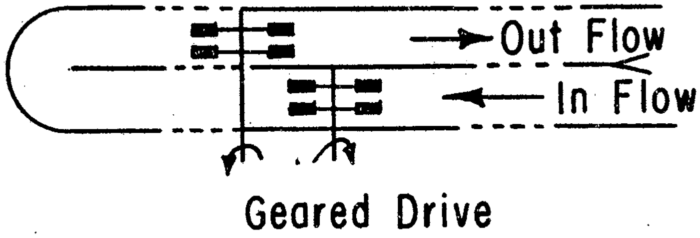
CHAPTER II

LITERATURE REVIEW

Both the aeration ditch and aeration tank have been used for waste treatment processes. The ASAE glossary on uniform terminology in farm waste management (2) defines an aeration tank as a tank in which sludge, sewage, or other liquid waste is aerated. There is no definition given for the aeration or oxidation ditch as it is sometimes called. Webb (37) explains this under the heading of aeration systems. The types of aeration systems are discussed of which one category is paddle wheels or surface beaters, Figure 1. It was then indicated that designs incorporating this principle could be used with a tank or ditch. There is no differentiation made between these methods except for the overall statement that liquid depth is not very deep in order to maintain a vigorous agitation and a general swirling of the aerated surface liquid into the body of liquid. It appears that the difference in the choice of these two general methods could be one of construction costs although Pasveer (30), in reporting on experiments with brush aeration, indicated that the process of aeration takes place entirely in the immediate vicinity of the brush, and that aeration proceeds more rapidly in a small tank or gutter than in a large tank, owing to the greater turbulence set up in the small tank.



(a) Side elevation of Kessener system.



(b) Plan view of Sheffield system.

Figure 1. Diagramatic Illustration of Paddle Wheel or Surface Beaters Shown by Webb (37).

The Oxidation Ditch

Walker (36) refers to the fact that sewerage treatment plants for large communities are complex. In addition to this, expert supervision is required. To scale such plants down for capacity and size does not result in a simplification of its operation or the process. This means that the cost of building and operating small sewage treatment plants is often prohibitive to developments or villages in the 100 to 5,000 population category. Reference is made to the extensive studies on small sewage treatment plants conducted by the Research Institute for Public Health Engineering of the Netherlands under the direction of Professor Dr. J. K. Baars.

Baars (4) states that the system of prolonged aeration of sewage in an oxidation ditch offers the possibility of full sewage treatment for small communities at the same proportionate cost as that of the conventional activated sludge system for large communities. This concept was described by Williams and Munson (39), Figure 2, as one of the new trends for the United States in the field of sewage treatment and its application in existing and future treatment problems.

Baars indicated that the process may be continuous or discontinuous depending upon the local situation and the quantity of sewage to be treated. Plants are in operation ranging in capacity from 200 to 4000 population, with a 7000 inhabitant plant being considered. He indicated that the system may be used, not only for domestic sewage, but also for dairy, potato starch, and other kinds of industrial waste. At present, it is not known what the maximum capacity of the oxidation ditch is.

In the United States, the Lakeside Engineering Corporation (22)

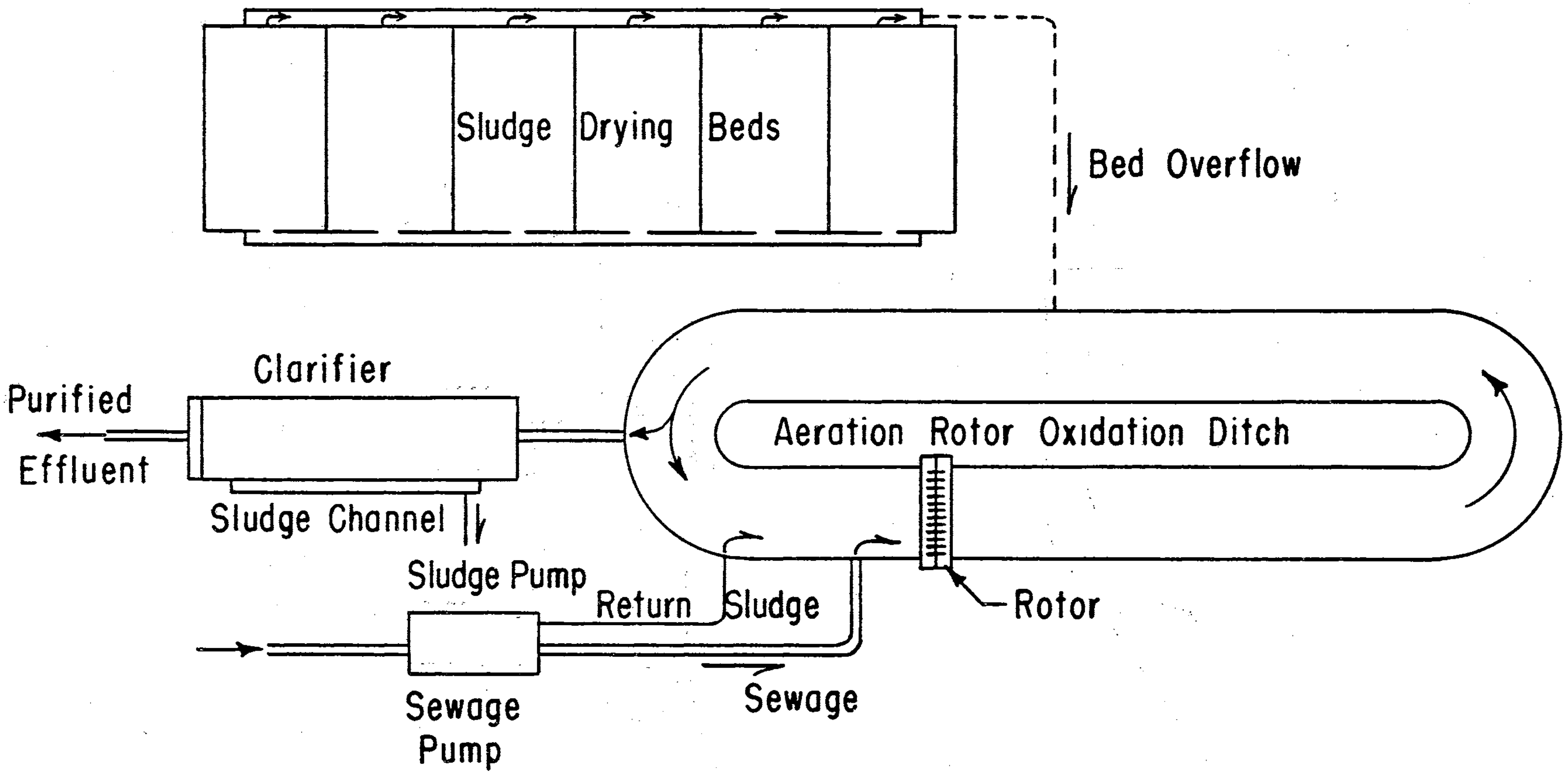


Figure 2. Oxidation Ditch schematic layout.

has adopted the oxidation ditch for use as a low cost sewage treatment plant. The system involves the use of a cage type rotor as an aeration device. The oxidation ditch used is laid out in the form of a race track. Its development has stemmed from the studies conducted by the Research Institute for Public Health Engineering of the Netherlands previously mentioned.

According to Williams and Munson (39) the oxidation ditch described is not an aerated lagoon. The cage rotor has a twofold function. First, it supplies oxygen to the slurry, and secondly, it provides the mechanism for slurry propulsion in the ditch. Their classification of the system is that it belongs in the extended aeration group of treatment processes. It is a modified form of activated sludge. The simplest type of installation possible is one having intermittent rotor aeration operation, Figure 3. When the rotor is stopped, the sludge in the ditch is allowed to settle and surface liquid drained off. There are other variations of the same system in which the rotor aerator operates continuously.

Okun (28), in his discussion of wastewater treatment in Europe, states that brush aerators produce a high efficiency of aeration and permit use of high solids concentration with resulting high efficiency. The reference to high solids concentration is applicable to agricultural wastes as can be observed from Hart's (13) summary of experiment results with dairy and chicken manure.

Aeration

The ASCE Sewage Treatment Plant Design Manual (3) classifies the methods of introducing air into sewage as being either diffused-air

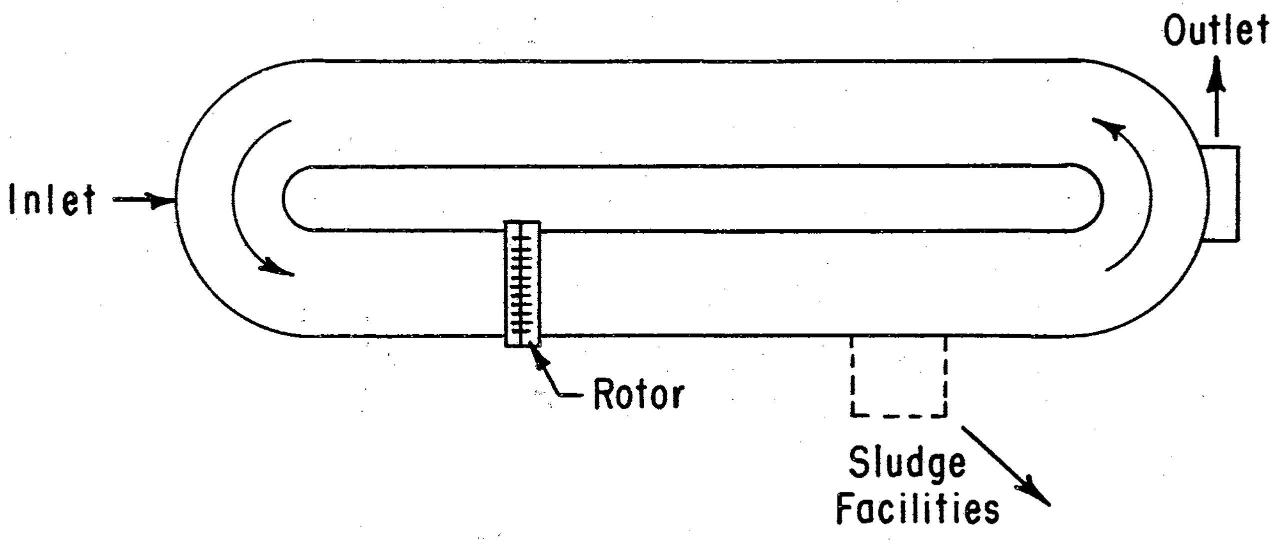


Figure 3. Basic oxidation ditch.

aeration or mechanical aeration. Diffused aeration is defined as aeration produced in a liquid by air passed through a diffuser.

Mechanical aeration is defined (3) as:

1. The mixing, by mechanical means of sewage and activated sludge, in the aeration tank of the activated sludge process, to bring fresh surfaces of liquid into contact with the atmosphere.
2. The introduction of atmospheric oxygen into a liquid by the mechanical action of paddle or spray mechanisms.

According to Eckenfelder (11), the main reason for aeration in a waste treatment process is to transfer oxygen. He states that oxygen transfer is usually accomplished by diffusion of air bubbles discharged from submerged orifices. In cases where high oxygen transfer rates are needed, a turbine is used to increase the turbulent mixing and the mass transfer rate. The rate at which this oxygen transfer occurs depends upon the:

1. Nature of the diffusion device.
2. Submergence depth.
3. Chemical nature of the waste mixture.
4. Air flow rate.

The last factor relates to diffused air processes where air is forced into the sewage being treated. This system involves the use of blowers, filters, compressors, air mains, laterals, feeder pipes, and diffusers (34).

The physical quantities for consideration in a mechanical aeration system were discussed by Kaplovsky, et al. (17). A broad list of variables were listed and then reduced to describe a particular system. Relationships were developed for the absorption rate per unit power for steady state conditions (constant flow rate). They stated that the method of dimensional analysis could lend assistance to future studies insofar as a comparison between systems would then be possible. It was indicated that dimensional analysis is a necessary approach wherever model studies are undertaken.

Hawkes (15) states that atmospheric oxygen must pass through four stages before it is utilized in the biological oxidation of waste. These are:

1. The transfer of atmospheric oxygen into solution in the waste water.
2. The transfer of the oxygen dissolved in the waste water to the surface of the respiring cell.
3. The diffusion through the cell wall and cell membranes into the cell itself.
4. The absorption by the appropriate respiratory enzyme.

The first two stages are of concern in waste treatment plant operation while stages 3 and 4 are governed by the properties of the cells themselves.

Krenkel and Orlob (21) examined the basic theories of the mechanism of gas transfer into liquids. They stated that there was general agreement except for the definition of the reaeration rate constant. The theoretical approaches to this aspect were limited by the indeterminate form of the parameters involved, and therefore experiments are required to predict the behavior of an aeration system in any practical situation. The authors indicated that the ever-growing pollution problem has brought an increasing urgency for solution of problems associated with the dispersive properties of liquids, and that the modern engineer must acquire an understanding of the diffusion process if he is to adequately cope with the situation.

Pasveer (29) reported that the rate of solution of oxygen in water in motion cannot be calculated without recourse to experiment; and that the rate of diffusion is inversely proportional to the square root of time. The latter factor was considered to be an important concept in any investigation of the diffusion process.

Downing and Truesdale (10) investigated a number of factors on the rate of solution of oxygen in fresh and saline waters to provide information about reaeration in a polluted estuary. It was shown that stirring water at different speeds with impellers or forcing air streams of different velocities tangentially over the surface caused relatively gradual changes in the rates of solution until the surface became visibly disturbed. After this, there was a much more rapid increase in the rate of solution with an increased rate of stirring or wind velocity. For different conditions of surface agitation, the rate of solution increased linearly with increasing temperatures in the range of 0 - 35°C.

Weston (38) reported on work with an entrainment aerator to better define the fundamentals of operation and to more precisely determine the effects of diameter, blade height and width, number of blades, speed of rotation, submergence and other variables on horsepower requirements and oxygen transfer. The entrainment aerator was a circular, flat plate with vertical blades extending radially from the periphery of the plate towards the center. In operation, the plate is rotated in a horizontal plane a short distance below the normal water surface. The results of these turbine operations were a transfer rate of 3.7 lbs. of oxygen per water horsepower-hour for low speed operation and

3.1 lbs of oxygen per water horsepower-hour for high speed operation. This was for tap water at 20°C and 0.0 ppm dissolved oxygen.

Sawyer (33) states that in aerobic biological treatment processes, the limited solubility of oxygen is of great importance because it governs the rate at which oxygen will be absorbed by the medium and, therefore, the cost of aeration. The low solubility of oxygen is a limiting factor in the purification capacity of natural waters. It is for this reason that waste materials from animals or humans must be processed* before their discharge into moving water bodies.

Oxygen Transfer Measurement

Kessener and Ribbius (19) evolved the concept of oxygenation capacity for an aeration tank. This was defined as the rate of oxygenation for deoxygenated distilled water at a temperature of 10°C and a barometric pressure of 760 mm, expressed in grams of oxygen per hour per cubic meter of aeration tank liquid volume.

Measurements of oxygenation capacity of an aeration system were made by the Netherlands Research Institute for Public Health Engineering (30). The procedure used was to fill an aeration tank with water. Oxygen was then taken out of the water by the addition of ferrous sulfate and sodium hydroxide solution. The chemicals and water were then mixed thoroughly. This was followed by the addition of air until there was a small amount of oxygen present in the water. Once the initial oxygen content was established, the aeration mechanism was placed in operation after which samples were taken at regular intervals for the

*According to the Engineer's Joint Council, "Thesaurus of Engineering Terms", the word "processing" is indicated as a use preference over the word "treatment".

determination of oxygen content.

Cooper (8) et al. studied the performance of agitated gas-liquid contactors using a sodium sulfite solution. These investigations involved vaned disks and flat paddles in geometrically similar, straight cylindrical tanks. The experiment procedure was as follows. Tap water at about room temperature was placed in the tank and the agitator started. Enough sodium sulfite crystals to make the solution approximately 1 normal in sulfite ion and cupric sulfate to produce a copper concentration of at least 10^{-3} molar were added and allowed to dissolve. The air was then turned on, and a timer was started when the first bubbles of air emerged from the gas dispersing device. The rates of oxygen absorption were measured by determination of the unoxidized sulfite-ion content of the solution before and after each run.

The Standard Methods for the Examination of Water and Wastewater (1) lists two methods for the determination of dissolved oxygen in a liquid: (1) chemical and (2) polarographic. For the chemical determination, there is a choice of methods available. This difference results from modifications that have been made to offset various ions and compounds which cause interference in the determination of dissolved oxygen. The polarographic method is suggested for use where the chemical methods are subject to serious errors in the presence of high concentration of industrial wastes.

There are now available commercially a number of instruments capable of measuring dissolved oxygen. These are essentially electrode probe type units separated by a gas permeable membrane material from the liquids or slurries being measured. An electrolyte provides the means for completing the electrical circuit between the anode and cathode. A thermistor is built into the probe for automatic temperature compensation. In using these probes, a minimum liquid or slurry flow velocity past the probe must be maintained.

Carritt and Kanwisher (7) reported on an electrode system for measuring dissolved oxygen. As compared to other procedures that have been used, the electrode system offers speed and simplicity. It can also be used with continuous recording units. An electrode system was selected for use in this study and is described further in Chapter IV.

CHAPTER III

THEORY

Theoretical Considerations

For a given type of rotor paddle mechanism and set of operating conditions, the rate of oxygen transfer from the atmosphere to a liquid or slurry at any time, t, will be dependent upon the concentration of the oxygen in the liquid initially, C_i, and the temperature of the liquid or slurry. During this oxygen transfer process, a point of equilibrium or saturation will be approached where the oxygen molecules entering the liquid and those escaping from it will be equal and constant. This is illustrated graphically by the upper end of the curve shown in Figure 4. The point at which this occurs will be dependent upon the physical limitations encountered in paddle system operation. The saturation level for dissolved oxygen in a liquid or slurry, C_s, for a given temperature and pressure is represented by the horizontal line.

In Figure 4, the slope of the curve is perhaps more meaningful in an evaluation of the rotor paddle mechanism for the oxidation treatment of agricultural waste. This is based upon the hypothesis that aerobic or facultative bacteria will utilize the dissolved oxygen of a liquid or slurry in the decomposition of organic matter (31). As this supply of oxygen becomes depleted, its replacement will be dependent upon mechanical aerator efficiency. The oxygen transfer by mechanical means will be influenced by the design of the rotor paddle mechanism and the

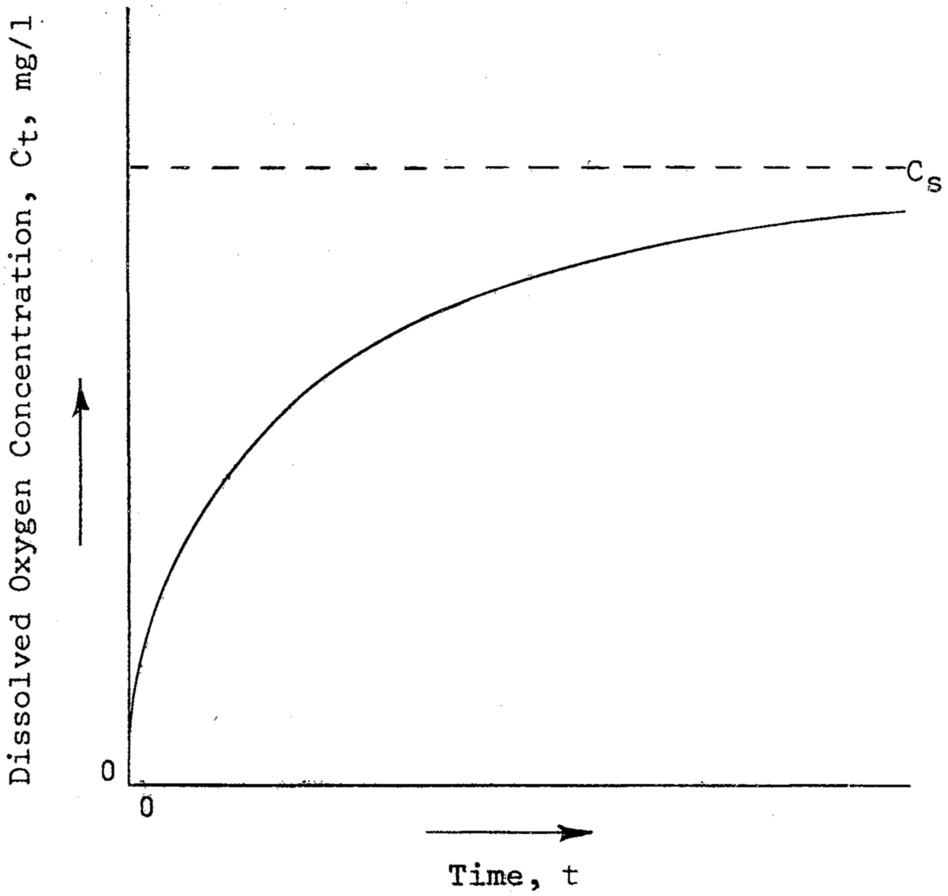


Figure 4. Hypothetical Relationship of the Effect of a Rotor Paddle Aerator on Oxygen Level in a Liquid or Slurry over a Given Period Time.

associated mechanism operating conditions. In addition, there will be an optimum level for bacteria environment, organic loading, and period of aeration which in turn must be related to the maximum mechanical aerator performance.

Haney (12) stated that there is no simple relationship between temperature and solubility in water. He indicated that adequate tabular data has been prepared on the subject. One source (1) gives a decrease of 0.8 mg/l in the solubility of oxygen in water exposed to water-saturated air in going from 68°F (20°C) to 77°F (25°C) at a total pressure of 760 mm of mercury. The amount of decrease is 0.7 mg/l if there are chlorides present in the water.

Eckenfelder (11) defined the mass transfer rate, R, of oxygen from air to water as being equal to the overall liquid film coefficient, K_L, times the area of interfacial contact between air bubbles and a liquid, A, times the dissolved oxygen deficit of a liquid. The latter term represents a subtraction of the dissolved oxygen concentration in the liquid initially, C_L, from the dissolved oxygen concentration at saturation, C_S, for a given temperature and pressure. The resulting equation is $R = K_L A(C_S - C_L)$. This is in agreement with what Lewis and Whitman (24) state earlier for the introduction of air into a tank. Eckenfelder's discussion was for bubble aeration in a column of water where surface aeration is neglected. The overall liquid film coefficient, K_L, was related to the velocity of the air bubble in its rise to the surface: the submerged depth of the air diffusing device in the liquid: and the rate of oxygen diffusion in the liquid or slurry. As it has been difficult to measure the interface area, A, Eckenfelder indicated that it has been an acceptable practice to combine the K_L and

A terms.

In the present study, the term oxygen transfer coefficient, OTC, represented the equivalent combination of the K_L and A terms used to describe diffused aeration. For a rotor aerator type paddle mechanism of the configuration and action shown in Figure 5, the expression, OTC, involves a ratio of the concentration of dissolved oxygen, C_t, in a given volume of liquid or slurry at any time, t_2, to the concentration of dissolved oxygen initially, C_i, and at time t_1. It is related to the level at which the given volume of liquid or slurry reaches its saturation point, C_s, for holding dissolved oxygen at a given temperature. The oxygen transfer coefficient can be developed from the expression

$$\frac{dC_t}{dt} = OTC(C_s - C_t)$$

where :

$\frac{dC_t}{dt}$ = the time rate of change in dissolved oxygen concentration at any time, t, and

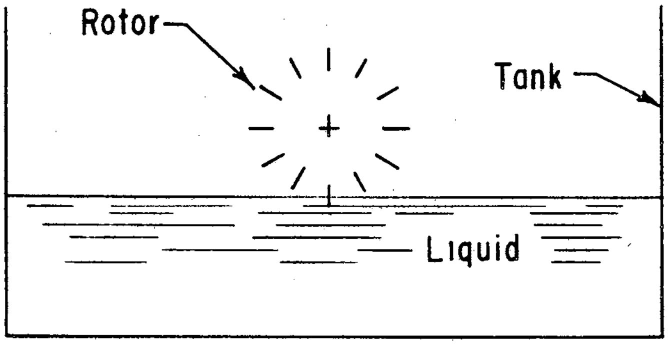
C_s and C_t are as previously defined having units of milligrams per liter, mg/l.

With C_t and t as variables, the general solution becomes:

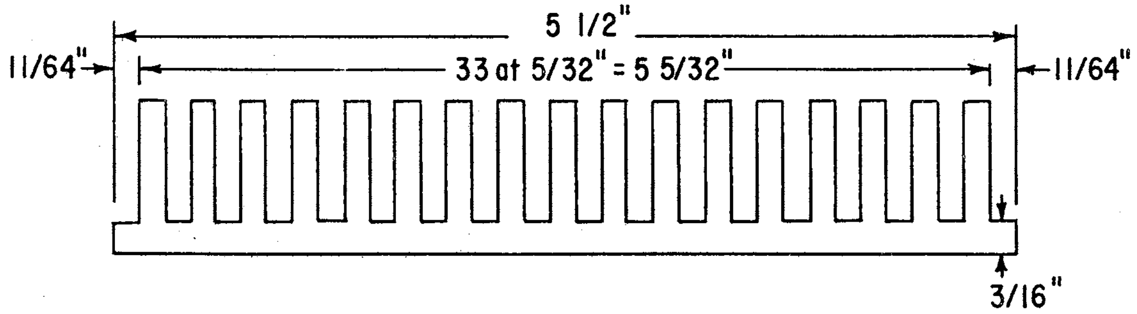
$$\int_{C_1}^{C_2} \frac{dC_t}{(C_s - C_t)} = OTC \int_{t_1}^{t_2} dt$$

where

C_1 and C_2 are respectively the dissolved oxygen concentrations, mg/l, at times t_1 and t_2.



(a) Schematic drawing of rotor aerator and tank.



(b) Paddle finger arrangement; blades alternately staggered.

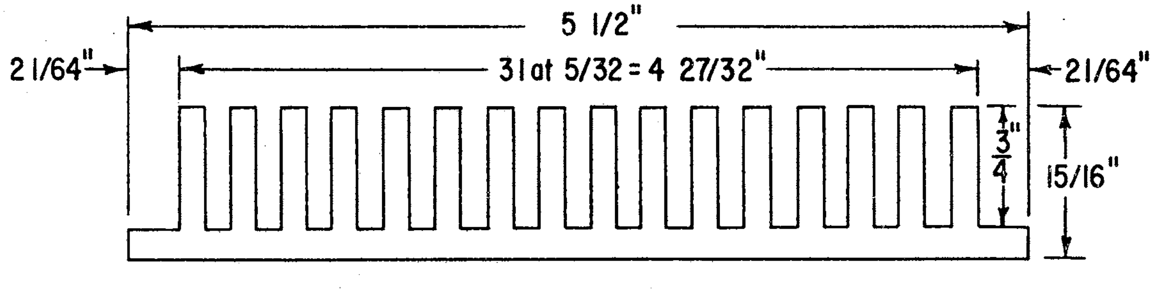


Figure 5

Integrating the above expression gives:

$$-\ln(C_s - C_t)\Big]_{C_1}^{C_2} = \mathrm{OTC}\cdot t\Big]_{t_1}^{t_2}$$

Substituting for C_t:

$$-\ln\left[\frac{C_s - C_2}{C_s - C_1}\right] = \mathrm{OTC}(t_2 - t_1)$$

which can also be written as:

$$-\ln\left[\frac{1 - {C_2}/{C_s}}{1 - {C_1}/{C_s}}\right] = \mathrm{OTC}(t_2 - t_1) = \mathrm{OTC}(\Delta t)$$

Rearranging terms gives:

$$\mathrm{OTC} = \frac{-\ln\left[\frac{1 - {C_2}/{C_s}}{1 - {C_1}/{C_s}}\right]}{\Delta t}$$

with OTC having the dimension of t^{-1}. According to this hypothesis, if a semi-logarithmic plot of the experimental data is made, then a straight line should be obtained. OTC will represent the slope of this line. If OTC is divided by the rotor aerator speed, N, which also has the dimension t^{-1}, a dimensionless parameter is obtained.

The oxygen transfer coefficient, OTC, thus found can be used to describe the effectiveness of a rotor type paddle mechanism in terms of its speed and paddle configuration.. The experiment conditions for the determination of this coefficient can be designed to also take into account variables such as liquid or slurry depth and the immersion depth of the paddle in the liquid or slurry. Related to these factors are the volume of liquid in the tank and the tank configuration. A rotor aerator paddle immersed in a large volume of liquid would require a longer period of time to change the dissolved oxygen content level of the liquid as compared to the same rotor aerator paddle being immersed in a lesser volume of liquid.

Theory of Similitude

Murphy (26) states that those principles which underlie the proper design and construction, operation, and interpretation of models of a prototype machine or structure comprise the theory of similitude. It includes a consideration of the conditions under which the behavior of two separate entities or systems will be similar, and the techniques of accurately predicting results on the one from observations on the other. This theory can be developed by dimensional analysis. He states that dimensional analysis is based upon two axioms:

1. Absolute numerical equality of quantities may exist only when the quantities are similar quantitatively.
2. The ratio of the magnitudes of two like quantities is independent of the units used in their measurement, provided that the same units are used for evaluating each.

In applying the theory of similitude, the experimental research is conducted on one system, the model. The observations made are then used to predict the performance of other systems, the prototype. According to Murphy (26), when these experimental procedures are combined with dimensional analysis, quantitative results and accurate prediction equations can be obtained.

With dimensionless analysis, the variables which are believed to influence the behavior of a physical system are first established. For the investigations made, and the type of rotor aerator paddle blade configuration selected, the physical quantities assumed to influence the rate of oxygen transfer per revolution of a paddle wheel in the mechanical aeration system described in Figure 5 are presented in Table I. The dimensions listed represent qualitative characteristics of physical measurements or observations.

The pertinent quantities of Table I, which must be measurable in physical units, are then combined to form dimensionless ratios referred to as Pi terms. According to Langhaar (23), the number of dimensionless products in a complete set will be equal to the total number of variables minus the rank of their dimensional matrix. Murphy (26) states that the only restriction placed upon Pi terms, in addition to being dimensionless, is that they be independent. The Pi terms developed for the system studied were:

$$Pi_1 = \frac{OTC}{N} \qquad Pi_5 = \frac{W_{at}}{W_r} \qquad Pi_9 = \frac{P_w}{S}$$

$$Pi_2 = \frac{L_{at}}{W_r} \qquad Pi_6 = \frac{P_{id}}{D} \qquad Pi_{10} = R$$

$$Pi_3 = \frac{Ne\rho ND^2}{\mu} \qquad Pi_7 = \frac{P_w}{D} \qquad Pi_{11} = \frac{W_r}{D}$$

$$Pi_4 = \frac{NeDN^2}{G} \qquad Pi_8 = \frac{d_\ell}{D}$$

Dimensionless Ratio Discussion

The dependent variable in this study was Pi_1, $\frac{OTC}{N}$, the rate of oxygen transfer per revolution of a paddle wheel. This represented a ratio of a unit volume of dissolved oxygen to a unit volume of the liquid or slurry per revolution of the rotor aerator. This relationship was discussed in more detail previously under theoretical considerations.

Pi_2, $\frac{L_{at}}{W_r}$; Pi_5, $\frac{W_{at}}{W_r}$; and Pi_{11}, $\frac{W_r}{D}$, represented the relationships of

TABLE I

PERTINENT QUANTITIES FOR A ROTOR-AERATOR SYSTEM

No.	Symbol	Identity	Dimension
1.	OTC	Oxygen transfer coefficient, 1/sec.	T^{-1}
2.	D	Rotor diameter, ft.	L
3.	P_{id}	Rotor paddle immersion depth, ft.	L
4.	P_w	Rotor paddle finger width, ft.	L
5.	d_ℓ	Liquid depth, ft.	L
6.	L_{at}	Aerator tank length, ft.	L
7.	W_{at}	Aerator tank width, ft.	L
8.	W_r	Rotor aerator width, ft.	L
9.	N	Rotor aerator speed, rps	T^{-1}
10.	S	Rotor paddle finger spacing, ft.	L
11.	R	Number of paddle blades on rotor shaft	—
12.	ρ	Liquid density, lb_m/cu.ft.	ML^{-3}
13.	μ	Liquid absolute viscosity lb_f - sec./sq.ft.	$FL^{-2}T$
14.	G	Gravitational effect, lb_f/lb_m	FM^{-1}
15.	Ne	Newton's second law coefficient lb_f/lb_m - ft./sec.^{2}	$FM^{-1}L^{-1}T^{-2}$

Dimensions: F = Force L = Length

M = Mass T = Time

Number of Pi terms = 15 - 4 = 11

the rotor aerator width to the liquid volume surface area and to the rotor aerator diameter. Except for Pi_{11}, $\frac{W_r}{D}$, these dimensionless ratios were held constant for the experiments conducted. Since rotor diameter was varied, the effect of variation in $\frac{W_r}{D}$ was neglected.

Pi_9, $\frac{P_w}{S}$, the ratio of paddle finger width to paddle finger spacing was 1.0 for all of the experiments. Its relation to the transfer of oxygen from air to liquid is in terms of liquid agitation. Haney (12) states that the agitation of a liquid decreases the resistance of the liquid to gas transfer. Pasveer (29) reported that the energy used for aeration should be directed toward the creation of a new water-air interfacial surface. The paddle blade finger arrangement contributes to the latter. These factors also apply to the number of paddle blades on a rotor shaft, Pi_{10}, R. If there were only two paddle blades as compared to the twelve paddle blades used in the study, at a given rotor aerator speed the dissolved oxygen content of the liquid or slurry would change more slowly. A rectangular shaped paddle blade finger was maintained but changes in the length and width dimensions were made when the remaining Pi terms were varied. The paddle blade thickness was held constant. A discussion of the rotor paddle blade configuration used in this study is described further in the chapter on apparatus and equipment.

The remaining Pi terms, Pi_3, Pi_4, Pi_6, Pi_7, and Pi_8 were treated as the independent variables for the observations made. In the remarks concerning each independent Pi term, it is assumed that all other factors remain constant.

Pi_3, $\frac{Ne\rho ND^2}{\mu}$, represents Reynolds number. It is an index of a ratio of inertia force to viscous force in the liquid. According to

Kaplovsky et al. (17), increased turbulence will increase the number of air-water interfaces and enhance oxygen transfer. For a given set of experiment conditions, as the rotor aerator speed, N, is increased, it would be expected that there be increased turbulence along with an increase in the rate of oxygen transfer.

Pi_4, $\frac{NeDN^2}{G}$, is the Froude number. It is an index of inertia to gravity forces. The inertia force is represented by the product $NeDN^2$. If gravity were not present, it would have been difficult to confine the liquid aerated to the experiment tank. Perhaps of equal importance is the role of gravity in the creation of buoyant forces which cause immersed bubbles to surface at some definite rate of movement.

Pi_6, $\frac{P_{id}}{D}$, is a ratio of the depth of the rotor paddle in the liquid to the rotor paddle diameter. As this ratio is increased, the rate of oxygen transfer should increase.

Pi_7, $\frac{P_w}{D}$, is a ratio of width of a rotor paddle finger to the rotor diameter. An increase in this ratio tends to increase the paddle-liquid contact area per paddle finger. It would also space individual paddle fingers further apart in a given line. In addition, there is a contributing effect to the oxygen transfer process from the action of alternate paddle finger spacing on adjacent paddles. This paddle finger arrangement is further described in the chapter on apparatus and equipment.

Pi_8, $\frac{d_\ell}{D}$, is a ratio of the depth of the liquid to the rotor paddle diameter. As this ratio is decreased, for a given rotor diameter, the volume of liquid being aerated will be less. Therefore, the aeration rate should increase.

In its simplest form, the relationship of the Pi terms can be expressed as a prediction equation in the form of:

$$Pi_1 = f(Pi_2, Pi_3, \ldots\ldots\ldots\ldots\ Pi_n)$$

The function which appears on the right-hand side of the general equation may denote any combination of Pi terms. If the rotor aerator system operation range conditions are satisfied, the prediction equation will be valid providing no significant pertinent quantities have been overlooked.

Murphy's procedure (26) for laboratory observations is that all of the Pi terms be held constant except one. This one Pi term is then varied while measurements of the phenomenon of interest are made. After completion of a range of observations for a given Pi term, a component equation is developed for this relationship. A similar procedure is then followed for the remaining independent Pi terms. The component equations are then combined to form a prediction equation. Depending upon the form of the component equation, the Pi terms can be combined by multiplication or summation to give a general prediction equation.

Theoretical Analysis

It is not possible to theoretically determine the oxygen transfer coefficient, OTC, for a given mechanical aeration system without first resorting to experimental data. Although this computation can be made in terms of assumed dissolved oxygen concentration levels at various time intervals, as per the hypothesis already outlined, there is no definite relationship established to a given type mechanical aerator. Therefore, experimental data must be collected on dissolved oxygen levels in a liquid or slurry for given system conditions in order to have a meaningful hypothesis. From these data, a prediction equation can then be developed which would permit computation of an oxygen transfer coefficient, OTC. The range of validity for this prediction equation would be dependent upon the range of values selected for the variables already described. This same prediction equation can be used to estimate the probable oxygen transfer coefficient in new applications for the type of system investigated. An example is the expected rotor aerator performance for processing of a number of different agricultural wastes providing the physical properties of material density and viscosity were known.

CHAPTER IV

APPARATUS AND EQUIPMENT

Model Rotor Aerator

A model paddle type rotor aerator, Figure 6, was constructed and mounted in a stainless steel container having transparent plastic side walls, Figure 7. The range of speed required for the rotor aerator was obtained through use of a variable speed drive, Figure 8, in conjunction with the use of pulleys and a V-belt. A stainless steel, U-shape channel was inserted inside of the aeration tank, Figure 9. The overall inside dimensions for the aerator tank were:

Length: 17.32"
Width: 8.66"
Depth: 11.02"

The height of the rotor aeration shaft was positioned as shown in Figure 10. A series of drilled holes at predetermined spacings and slotted holes in the shaft support assembly, Figure 10, were used to obtain the height adjustments needed. A gasket was secured to the inside of the shaft support assembly to prevent leakage. The shaft support assembly was positioned on the outside of the aeration tank and held in place by stove bolts.

Details of the rotor paddle blade configuration are shown in Figure 11. The various sizes of paddle fingers used in the experiments are presented in Table II.

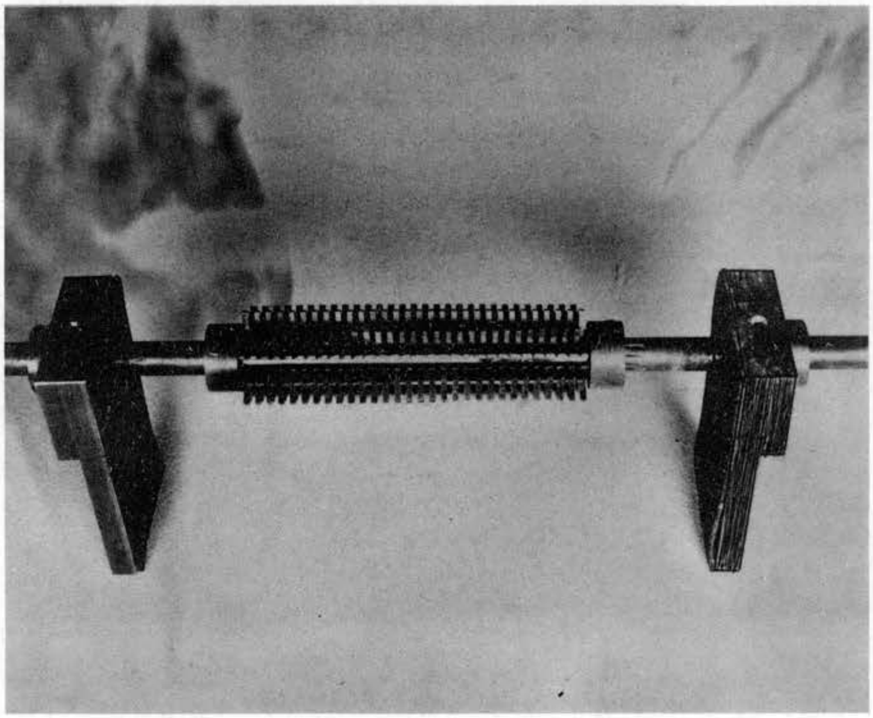


Figure 6. Model Rotor Aerator Paddle Mechanism.

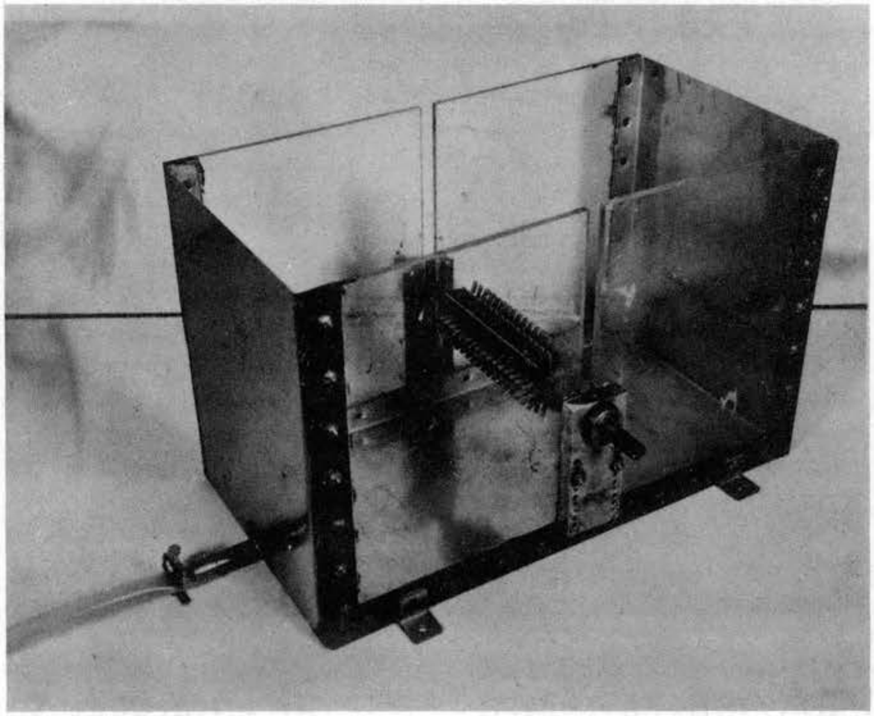


Figure 7. Experiment Aeration Tank.

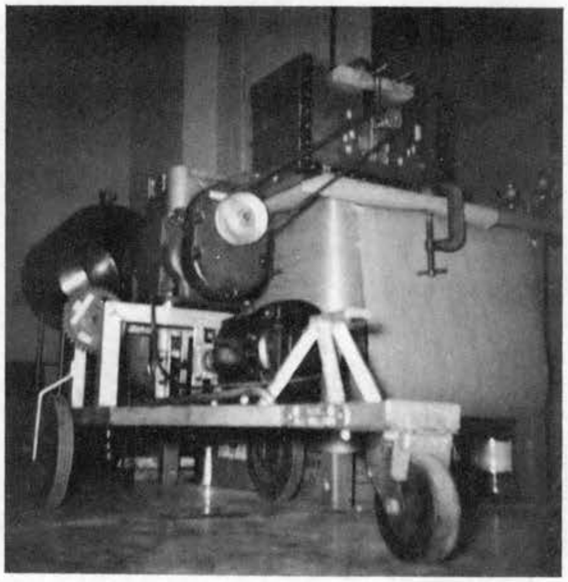


Figure 8. Rotor Experimentation Set-up Showing Variable Speed Drive and Aeration Tank. The Check Tank Used With the Experiment is in the Background.

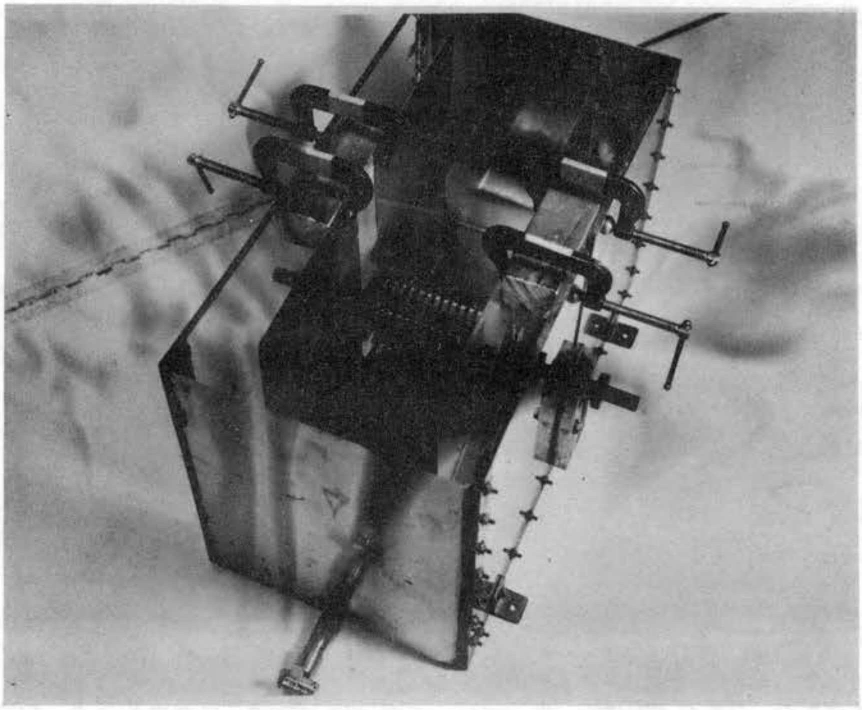


Figure 9. Position of U-Shape Channel in Aeration Tank and Method of Holding Channel in Place. View is from Top Looking Down into the Aeration Tank.

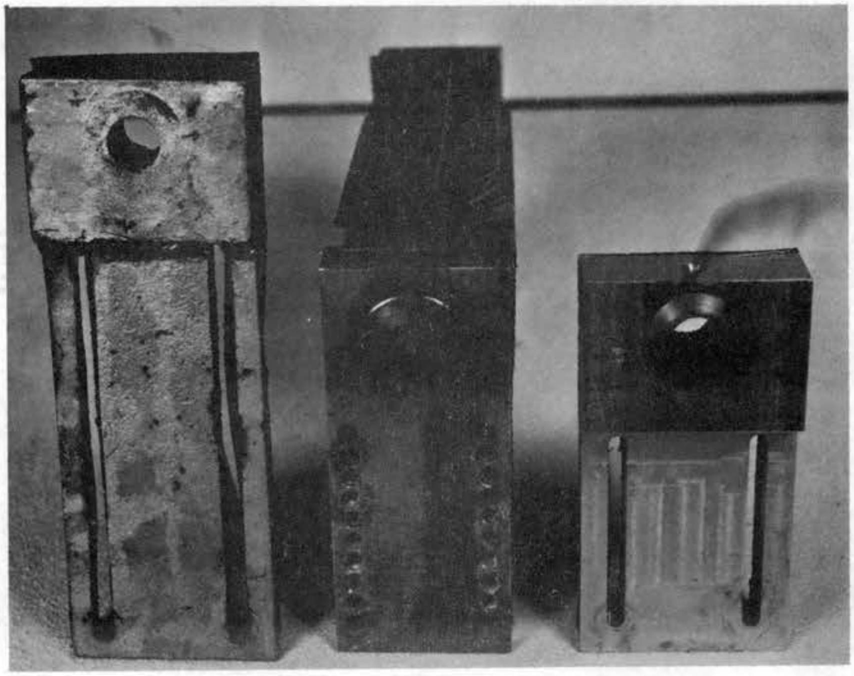


Figure 10. End View of Rotor Aerator Shaft Support Assembly; Both a Slot and Series of Drilled Holes Were Used for Shaft Height Position Control.

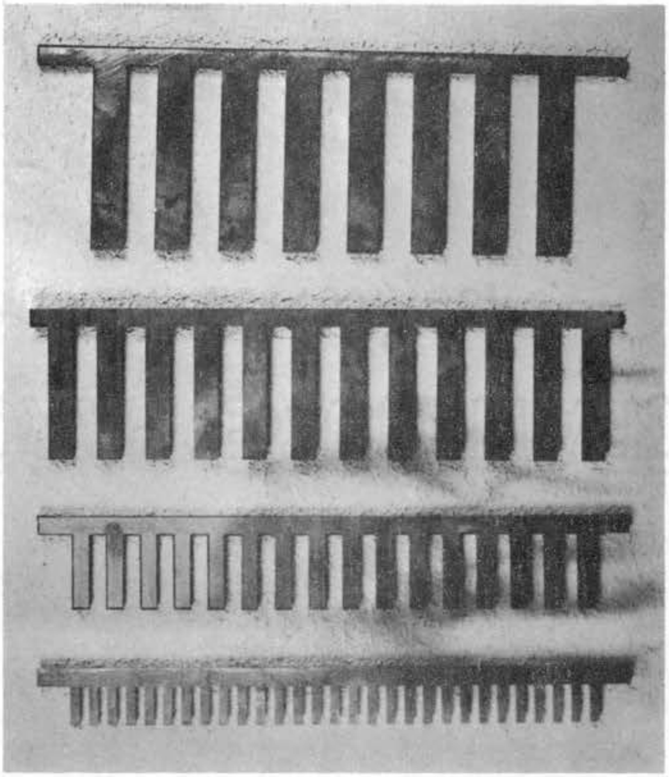


Figure 11. Rotor Paddle Blade Showing Staggered Arrangement of Fingers and Comparative Sizes.

TABLE II

ROTOR PADDLE BLADE FINGER DIMENSIONS

Length inches	Width inches	Spacing inches
1.75	0.297*	0.297*
1.25	0.225	0.225
0.75	0.156	0.156
0.75	0.25	0.25
0.75	0.50	0.50
0.375	0.086	0.086

* Calculated value was 0.294. Dimension change was for machining convenience.

Each paddle blade was inserted into a 1/16" x 1/16" keyway on the shaft. The keyways were spaced at 30 degree intervals on the shaft circumference. A recessed collar was used at both ends to assist in paddle blade assembly initially and to secure the paddle blades on the shaft. Two arrangements for paddle fingers were used, e.g. alternate paddle blades had fingers positioned at staggered locations. The entire assembly consisted of twelve paddle blades per rotor shaft.

The $\frac{1}{2}$" rotor shaft rode in oil-impregnated bronze bearings which were press-fitted into pillow blocks. The pillow blocks were fastened to the shaft support bracket with machine screws. Solid steel shaft collars, with set screws, held the rotor aerator in position with relation to the aerator tank.

Instrumentation

A Jarrell-Ash dissolved oxygen analyzer was used for dissolved oxygen measurement. A cross section of the electrode probe assembly (16) and its components are shown in Figure 12.

According to the above cited source, this electrode assembly

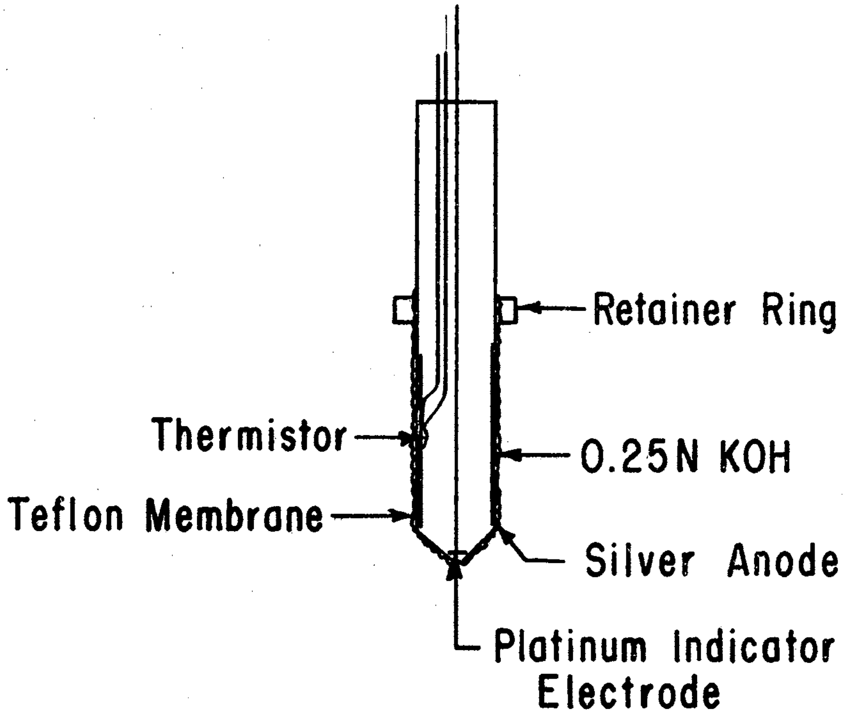


Figure 12. Cross section of electrode assembly.

functions as follows. The teflon membrane is permeable to dissolved oxygen but much less to other dissolved substances. When the oxygen diffuses through the membrane, it reacts at the platinum electrode to be reduced to hydroxyl form. The hydroxyl ions diffuse to the silver anode reference electrode to form a silver oxide surface. When the silver oxide makes contact with the internal potassium hydroxide electrolyte, a circuit path is completed to the platinum electrode and a current signal produced. This current signal is proportional to the amount of oxygen reduced. A thermistor built into the probe provided automatic compensation for changes in temperature.

Due to the fact that oxygen diffusion in a liquid sample is slow, a minimum flow of 1 cm/sec. should be maintained at the tip of the dissolved oxygen analyzer probe. A magnetic stirrer (E. H. Sargent and Co. Cat. No. S-76490) was used in the laboratory for this purpose.

CHAPTER V

EXPERIMENTAL PROCEDURE

Experiment Design

Referring to the Pi terms developed in Chapter III, the expression for the prediction equation to describe the effectiveness of a rotor aerator for oxygen transfer from air to liquid was:

$$\frac{OTC}{N} = f\left(\frac{Lat}{Wr}, Re, Fr, \frac{Wat}{Wr}, \frac{Pid}{D}, \frac{Pw}{D}, \frac{d_\ell}{D}, \frac{Pw}{S}, R, \frac{Wr}{D}\right).$$

Of the independent Pi terms, $\frac{Lat}{Wr}$, $\frac{Wat}{Wr}$, $\frac{Pw}{S}$, and R were held constant and the effect of variation in $\frac{Wr}{D}$ was neglected. Eliminating these five Pi terms, the prediction equation to describe the effectiveness of a rotor aerator for oxygen transfer from air to liquid was reduced to:

$$\frac{OTC}{N} = f\left(Re, Fr, \frac{Pid}{D}, \frac{Pw}{D}, \frac{d_\ell}{D}\right).$$

The experimental schedule followed is given in Table III and was based upon the performance range that could be expected in a prototype rotor aerator.

A total of 34 tests were conducted. The test sequence followed is given in Appendix A.

In the experiments involving Reynolds Number and the Froude Number, the rotor diameter was varied to obtain the desired experiment design. If the Reynolds Number value was changed, then the Froude Number value was held constant by an adjustment in paddle wheel speed.

TABLE III

EXPERIMENT DESIGN

OTC	Re#	Fr#	P_{id}/D	P_w/D	d_1/D
Observed Response	Vary D 1.25" 2.25" 3.25" 4.25"	Adjust N 0.1456	Adjust P_{id} 0.167	Adjust P_w 0.0693	Adjust d_1 1.68
	Adjust N 16671	Vary D 1.25" 2.25" 3.25" 4.25"	As above	As above	As above
	16671	0.1456	Vary P_{id} 1/8" 3/8" 5/8"	0.0693	1.68
	16671	0.1456	0.167	Vary P_w 5/32" 1/4 " 1/2 "	1.68
	16671	0.1456	0.167	0.0693	Vary d_1 3 25/32" 4 25/32" 5 9/32" 5 25/32"

For example, when the rotor paddle diameter, D, was changed to 4.25 inches to vary Pi_3, Reynolds Number, the value of all the other Pi terms in which a D term appeared was effected. An adjustment to one or more of the other pertinent quantities in each of these Pi term expressions was necessary to keep these values constant. For the Froude Number, this was controlled by calculating the speed, N, necessary to keep this value from changing. In this case, the calculated rotor aerator speed was determined to be 218 rpm or 3.63 rps. This was then the rotor aerator speed for which measurements of the dependent parameter, $\frac{OTC}{N}$, were made when the Reynolds Number, Pi_3, was varied. As might be noted here, the paddle finger width and spacing also had to be modified because of the change in rotor diameter, D, if Pi_7, $\frac{Pw}{D}$, were to remain unchanged. This value was determined to be 0.294 inches and is given in Table II and the paddle blade described is shown in Figure 11a. Similarly the calculated values for paddle immersion depth was 0.703 inches in Pi_6, $\frac{Pid}{D}$, and for the liquid depth in the aerator tank was 7.09 inches in Pi_8, $\frac{d\ell}{D}$. A summarization of values for the corresponding tests conducted are presented in the experiment sequence of Appendix A under Test Nos. 4 and 5.

Similarly when the Froude Number, Pi_4, was changed, the speed necessary to hold the Reynolds Number, Pi_3, constant was calculated. For a 4.25 inch diameter rotor, the computed speed, N, was 83.6 rpm or 1.4 rps. The remaining Pi terms were the same as previously computed. These data are summarized under Test No. 6 in the Experiment sequence of Appendix A.

In the scheduling of the test sequence for the first series, the Pi_7, $\frac{Pw}{D}$, tests were last due to the fact that the paddle blades required for these observations were not available until then. As some equipment modification was involved with the Pi_8, $\frac{d}{D}\ell$, tests, the second series preceded the Pi_7 tests as a precautionary measure.

Experiment Technique

Distilled water was used for the study. Preliminary investigations with dairy feces and urine indicated that too many variables would be introduced if this material were used. For example, there was little control over the source of manure supply available. This would have had to come from different animals subject to different feeding programs. Animal diet also changes the characteristics of the excretion leaving an animal. For example, a high concentrate feeding program will probably result in a soupier feces than that from an animal which has been on a high roughage feeding program. The latter feces would be more fibrous containing more lignin. Basic information on waste material physical properties, such as combined feces and urine viscosity, was lacking. It was not known what the maximum loading rate or detention period should be. The additional data required would have expanded the investigation beyond the intended scope of study.

A generalized prediction equation is valid if its range encompasses the prototype system. Although the density and viscosity of a slurry manure are not known now, a generalized prediction equation presumably could be used to predict rotor aerator performance in liquid manure, even though the experiments were done with water.

The dissolved oxygen analyzer was calibrated at the 0 percent oxygen level and at 100% oxygen saturation. Four different checks were made: aerated water; non-aerated water; boiled water; and water to which sodium sulfite was added. Of each sample, approximately 250-300 ml was transferred to BOD bottles for this purpose. In addition, the Alsterberg (Azide) modification of Winkler method described in Standard Methods for the Examination of Water and Wastewater (1) was used to determine the dissolved oxygen content of duplicate samples of the aerated and boiled water. The latter provided assurance in the reliability of the results being obtained.

Prior to the start of each experiment, both the check tank and aerated tank were filled with equal volumes of water. The purpose of the check tank was to determine whether or not there was any transfer of oxygen across the air-water interface during the experimental observation. A Centigrade thermometer was immersed in the check tank and the water temperature was observed prior to the start of test, at intervals during the test, and upon cessation of the experimental observation.

Sodium sulfite was added to the aeration tank in the ratio of $\frac{1}{4}$ gram to 1 liter of distilled water. This figure was arrived at by taking 1 liter of distilled water and adding $\frac{1}{4}$, 1, 3, and 4.6 grams to each sample. These solutions were mixed first with a hand stirrer and then with a magnetic stirrer until the powdered sodium sulfite solution had disappeared. A 500 ml sample was drawn off and the four samples mounted on an Hipps and Bird Laboratory Stirrer (Ser. No. 2.678, Richmond, Va.). A period of 13 minutes elapsed before the stirrer was turned on. After approximately thirty minutes of stirring at one-half speed, the dissolved oxygen measurement for the $\frac{1}{4}$ gm $NaSO_3$/liter container was at about 1%. As would be expected, the solutions in the other beakers required a longer mixing period. It was concluded that $\frac{1}{4}$ gm $NaSO_3$/liter would suffice for the experiment conditions as initially there would be no aeration of the solution until the start of test. The main concern was to have a zero condition for dissolved oxygen at the start of the experimental observation, and not to have too long a rotor aeration test period at the zero dissolved oxygen level due to the quantity of sodium sulfite added to the distilled water. To illustrate this point further, with the 4.6 gm $NaSO_3$/liter of distilled water, the dissolved oxygen level of the solution after eight hours of stirring was still zero.

The volume of water required for each experiment was calculated from the predetermined liquid depth and the inside area of the aeration tank. After a given quantity of water had been added to the aerator tank, a series of taped reference levels were established on the transparent sides of the tank. The required amount of sodium sulfite was added, and the rotor aerator run briefly to speed solution of the powder into the water. A waiting period followed before an experimental observation was started. This was generally for about forty minutes.

Before the start of each experimental observation, standard BOD bottle samples of water (250-300 ml) were removed from both the aeration and check tank for dissolved oxygen measurement. To compensate for the removal of this quantity of water, an equal amount of distilled water was added to both tanks, initially, in addition to the volume calculated for the experiment. After the measurement was made, the sample was not returned until first a new sample had been withdrawn from the tanks. This meant that the liquid depth in the aerator tank was decreased slightly during this period. Most of the measurements were made at approximately two minute time intervals. When the rate of change for dissolved oxygen concentration in the liquid began to show signs of decreasing, a greater time interval on measurement was used. These measurements were then stopped after it had been established that sufficient data had been collected to indicate the leveling off effect shown in Figure 4.

CHAPTER VI

ANALYSIS OF DATA

Under normal atmospheric conditions, assuming that a liquid has no dissolved oxygen present in it initially and that it is then subjected to aeration by mechanical means, the hypothetical results described earlier by the curve of Figure 4 can be expected. The slope of the curve will be dependent somewhat upon the efficiency of the mechanical aerator system in its operation. Ideally, it would also be desirable for the dissolved oxygen concentration curve to reach the saturation level for dissolved oxygen in a liquid at a given temperature. In Figure 4, this is represented by the horizontal line, C_s.

However in practice this ideal condition of liquid saturation for dissolved oxygen concentration, C_s, will not be achieved, ideally or practically, even if the OTC is constant, because:

$$\mathrm{OTC} = \frac{\mathrm{Ln}\left[\frac{C_s-C_t}{C_s-C_i}\right]}{\Delta t}$$

so:

$$\mathrm{Ln}\frac{C_s-C_i}{C_s-C_t} = \mathrm{OTC}(\Delta t)$$

or:

$$\frac{C_s-C_i}{C_s-C_t} = e^{\mathrm{OTC}(\Delta t)}$$

so:

$$e^{-\mathrm{OTC}(\Delta t)}\left[C_s-C_i\right] = C_s-C_t$$

or:

$$C_t = C_s - \left[C_s - C_i\right] e^{-(OTC \times \Delta t)} = C_s - \frac{C_s - C_i}{e^{OTC \times \Delta t}}$$

Thus, C_t will never, in finite time, equal C_s. This observation is made independently of any system limitations.

The experimental data when plotted on semi-log paper was of the form shown in Figures 13 and 14. For the straight line portion, this is the type of relationship that one would expect according to the analysis developed on page 22. Davis (9) in a discussion of fundamental forms of empirical equations states that such a plot of data on semi-logarithmic paper suggests an empirical equation of the form $y = 10^{a+bx}$ for the straight line portion.

The data of Figures 13 and 14 do not fit a straight line beyond a certain point. This departure from a linear plot occurs because the oxygen transfer coefficient, OTC, is no longer constant. The reason for this could be the physical limitations of a given type rotor aerator system. A study of the purpose behind the mechanical aeration of a liquid or slurry would indicate that one of the prime considerations is the acceleration in the transfer of oxygen from air to a liquid or slurry. For the experiments conducted, this factor is reflected by the value of OTC obtained. A high OTC value would mean a rapid transfer of oxygen from the air to a liquid and a low OTC value would be the opposite in meaning. Therefore, it becomes necessary to establish a representative value for OTC in relation to the liquid dissolved oxygen concentration level at equilibrium or saturation.

In the experiments conducted, it was necessary to determine the line slope cut-off or breaking point for data of the form shown in Figures 13 and 14. This was to say that rotor aerator performance could

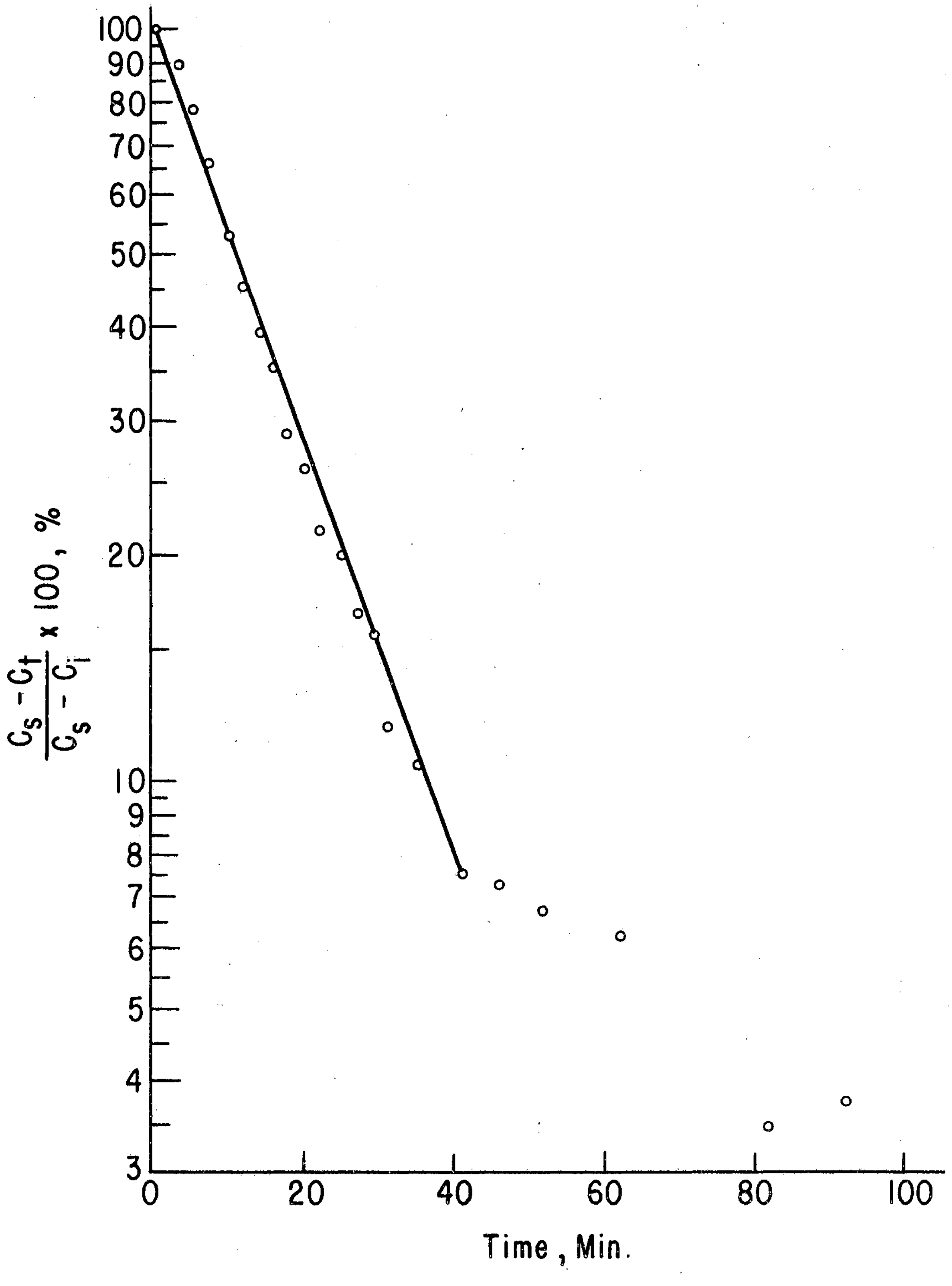


Figure 13. Example of experimental data plot observed.

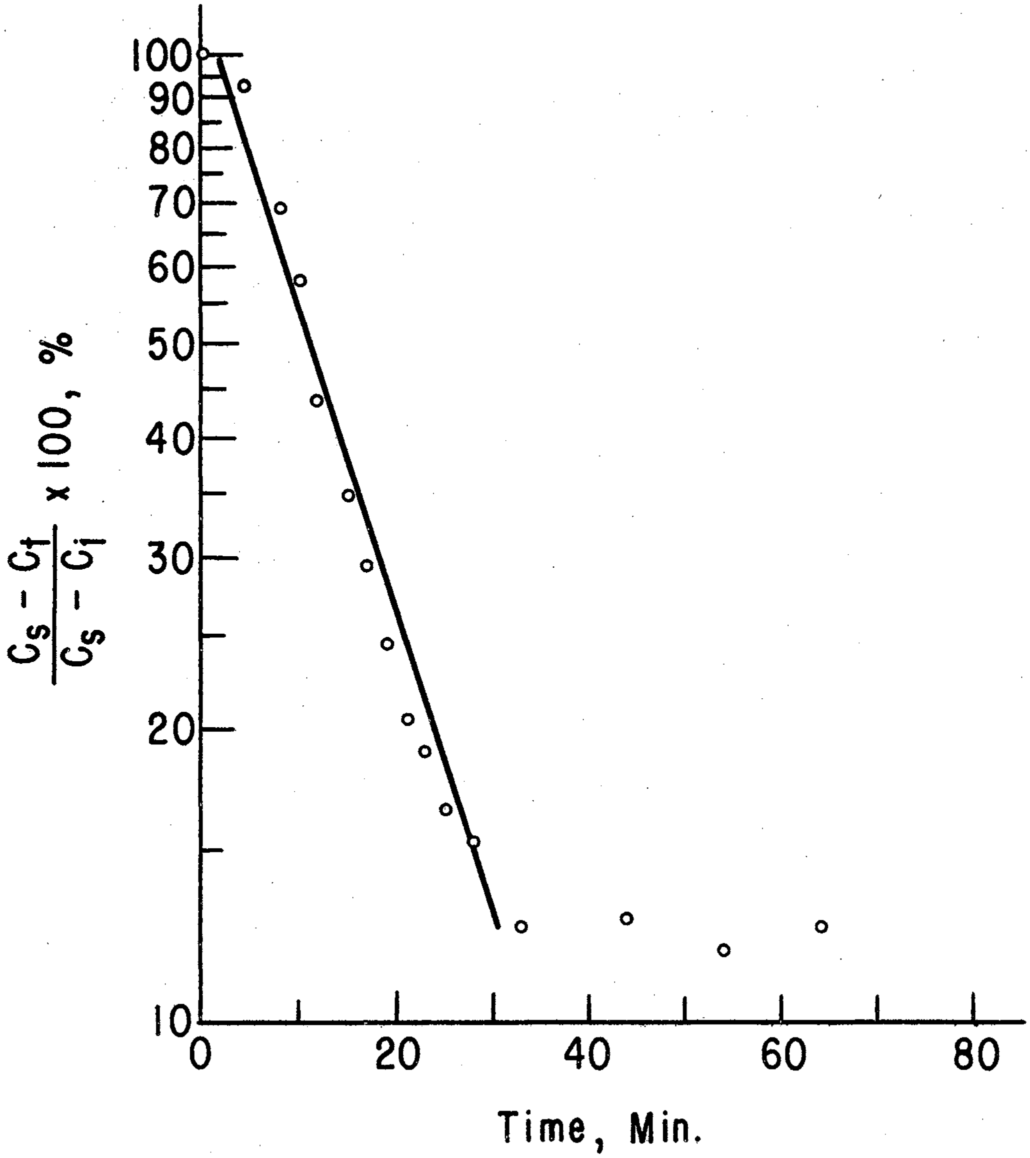


Figure 14. Example of experimental data plot observed.

be evaluated from data obtained in the region going from zero dissolved oxygen concentration in a liquid to a dissolved oxygen concentration level where liquid equilibrium or saturation is being approached. The latter part is the flat or asymptotic portion of the curve shown in Figure 4. This part of the curve is not as critical when it comes to selection of a rotor aerator for system applications. It would seem that once the equilibrium or saturation point for concentration of dissolved oxygen in a liquid or slurry has been reached or maintained, the desired goal for system performance has been achieved. The question of greater importance is the transfer of oxygen from air to liquid or slurry in terms of the design oxygen requirement of a system. For example, the oxygenation capacity of a rotor aerator for an animal waste processing installation might be 2.5 lb/day. A rotor aerator can then be evaluated in terms of oxygen transfer coefficients for varied system operating conditions to determine whether or not it will satisfy the requirement indicated.

The method chosen to determine the line slope, OTC, for the experiment data, such as that shown in Figures 13 and 14, is described as follows. Starting with the first three measurements for which dissolved oxygen values greater than zero were observed, the line slope was determined and this computation repeated for each observation thereafter. This analysis was made using a digital computer. For each line slope, the error mean square of regression was found and the difference between the error mean square for each successive observation was obtained. Sample data are shown in Table IV. When the error mean square of regression incremental difference appeared to take a sudden change, this was the point selected for breaking the line slope. Data beyond

TABLE IV

LINE SLOPE SELECTION PROCEDURE

Error Mean Square of Regression x 10^{-4}	Incremental Difference x 10^{-4}	Time, mins.
7.51		24
	0.45	
7.06		27
	0.48	
6.58		29
	1.88	
8.46		31
	0.59	
7.87		34
	0.78	
7.09		36
	0.48	
6.61		38
	0.83	
5.78		41
	0.63	
5.15		43
	0.64	
4.51		45
	0.36	
4.15		47
	0.30	
3.85		49
	0.23	
3.62		52
	0.14	
3.48		54
	0.18	
3.3		56
	0.4	
3.7		60
	1.2	
4.9		64
	1.3	
6.2		68
	2.3	
8.5		74
	3.4	
11.9		79
	7.1	
19		85
	7.6	
26.6		91

this point was not used and was considered as being more representative of the flatter or asymptotic portion of the curve type such as is shown in Figure 4. Using the method described permitted the inclusion of some of the data from the transitional region between the straight line and the flat portion of the type curves already discussed. The resulting OTC value is a more conservative one for describing rotor aerator system effectiveness than would have been obtained if the OTC value were selected at the time period where the lowest error mean square of regression was determined. However, in terms of a relative comparison of the performance for different type rotor aerators, the findings will be similar.

In Table IV, the greatest incremental difference occurred in going from the 79 minute to the 85 minute time period. The incremental difference for the error mean square values obtained changes from 3.4 to 7.1. In this case, the slope of the line, OTC, was selected as that value obtained at the 79 minute time period. The slope of the line for each of the experiments conducted, and its corresponding correlation coefficient obtained in this manner are given in Appendix B.

For the data of Table IV, the OTC value obtained by the error mean square of regression incremental difference was -1.026. If the alternate method of OTC selection based upon the lowest error mean square of regression were used, the OTC value would be -1.33. In Table IV, for the latter, this would correspond to the measurements made over a 56 minute time period.

OTC, the line slope obtained from each experiment was divided by the speed, N, to give a dimensionless term. These values were then plotted against the various independent parameters on log-log paper.

According to the procedure given by Murphy (26) which was described earlier, if the data plotted as a straight line on log-log paper, the component equations could be combined by multiplication. For the data plotted, it was hypothesized that this relationship existed and a linear regression analysis of the data was made. These values and the corresponding correlation coefficients obtained are presented in Table V.

TABLE V

COMPONENT EQUATION SLOPES AND CORRELATION COEFFICIENTS

Independent Parameter	Slope	Correlation Coefficient
Pi_3, Reynolds Number	0.700	0.983
Pi_4, Froude Number	-0.187	0.958
Pi_6, Paddle immersion depth/Rotor diameter	0.856	0.987
Pi_7, Paddle finger width/Rotor diameter	0.183	0.995
Pi_8, Liquid depth/Rotor diameter	-0.275	0.996

The resulting prediction equation for the component equation results when combined by multiplication was:

$$\frac{OTC}{N} = (7.42 \times 10^{-7}) \left[Re^{(0.700)} \times Fr^{(-0.187)} \times \left(\frac{Pid}{D}\right)^{0.856} \times \left(\frac{Pw}{D}\right)^{0.183} \times \left(\frac{dl}{D}\right)^{-0.275} \right]$$

The Pi terms $\frac{L_t}{W_R}$ and $\frac{W_t}{W_R}$ were not included since the aerator tank length, L_t, and width, W_t, along with the rotor aerator width, W_R, were held constant for all of the experiments. The numerical values for these two Pi terms were 3.36 and 1.68 respectively. The aerator rotor end effects were ignored. Therefore, the Pi term $\frac{W_R}{D}$ was dropped from the prediction equation.

CHAPTER VII

DISCUSSION AND APPLICATION OF RESULTS

A comparison of the predicted values and the observed values for the rotor aerator studied is given in Figure 15. The 45 degree line represents where the points would be located if each predicted value and the corresponding observed value were in perfect agreement. A linear regression analysis of this data was made to determine the line of best fit, its slope, line intercept, and correlation coefficient. These values were 1.44, -0.0000514, and 0.917 respectively.

The two points at the top of the plot in Figure 15 were for experiments number 4 and 7. In both instances, it was the Pi term for Reynolds number, Pi_3, which was being varied. Some of the discrepancy here between the observed and predicted data may have been due to experimental technique or error. A noticeable difference was observed in the aerator tank liquid agitation between experiments number 4 and 5. Both of these tests involved a variation in the Reynolds number, Pi_3, for similar conditions. For experiment 4, the liquid agitation action could be described as being vigorous whereas with experiment 5, there appeared to be a more gentle, stirring action of the liquid in the aeration tank. For both experiments 4 and 5, the rate of oxygen transfer from the air to the liquid was rapid during the early stage starting from the initial condition of zero dissolved oxygen content. The amount of time for frequency between sampling and measurement of dissolved oxygen was limited

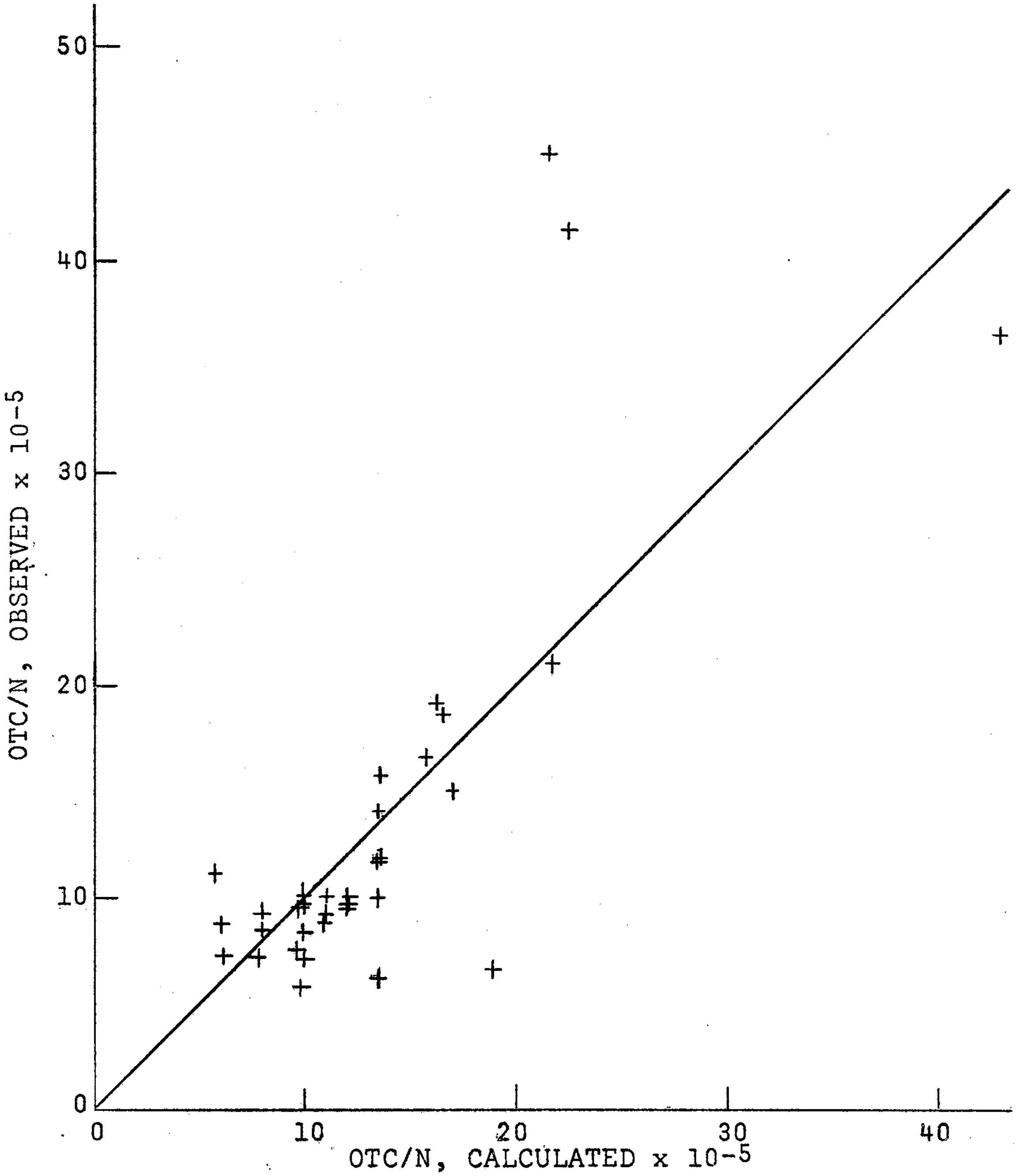


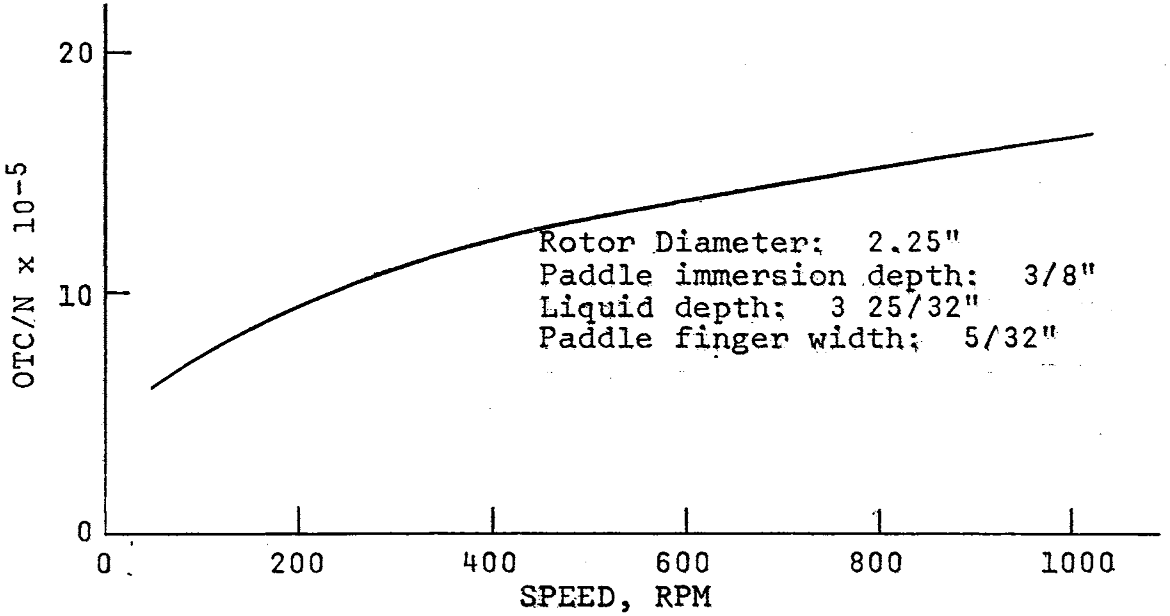
Figure 15. Observed OTC/N Versus Calculated OTC/N.

to intervals of two to three minutes and possibly this factor could have contributed to the difference shown. If dissolved oxygen measurements could have been made at intervals of one minute or less, such data would have helped to better describe the rate of change in the dissolved oxygen content of a liquid where this process was occurring more rapidly. This was not possible to do for the way in which the experiments were conducted.

In the engineering design of a rotor aerator, the rate of oxygen transfer per paddle revolution for varied application conditions is of interest. A prediction equation of the form developed can be used to determine the effects of such variables as rotor speed, paddle wheel diameter, liquid or slurry depth, or certain changes in paddle wheel configuration. A similar evaluation can be made for different liquids or slurries. Examples illustrating these applications follow.

The curve of Figure 16 was plotted from OTC/N computations made for model rotor aerator speed increments of 50 rpm starting at this value and ending at 1000 rpm. This covered the experiment paddle aerator speed range used which was from 83.6 rpm to 966 rpm. A similar computation was made for a prototype rotor aerator having a diameter of 27 inches. The resulting curve plot obtained, Figure 17, was similar except that the OTC/N values were larger. These ranged from a value of 1.25×10^{-3} at 50 rpm to 3.33×10^{-3} at 1000 rpm. The same numerical ratios of the model were used for Pi_6, $\frac{Pid}{D}$; Pi_7, $\frac{Pw}{D}$; and Pi_8, $\frac{d_1}{D}$.

When the rotor aerator speed is changed, Figure 16, both the Reynolds and Froude number, along with the dependent Pi term, OTC/N, will be affected in the prediction equation but not the other independent Pi terms. As might be expected if one were to examine the prediction equa-



Rotor Diameter: 2.25"
Paddle immersion depth: 3/8"
Liquid depth: 3 25/32"
Paddle finger width: 5/32"

Figure 16. Effect of Speed on Rotor Aerator Rate of Oxygen Transfer: Model Conditions.

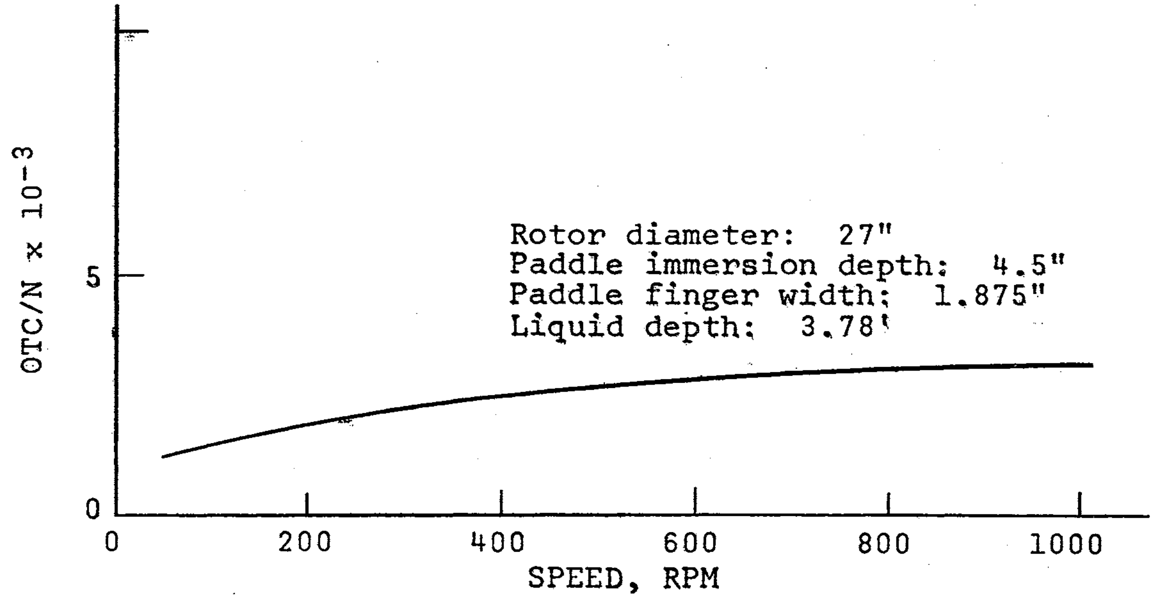


Figure 17. Effect of Speed on Rotor Aerator Rate of Oxygen Transfer: Prototype Conditions.

tion more closely, an increase in rotor speed will result in an increase in the value of OTC/N, the oxygen transfer coefficient per revolution of the rotor.

A further examination of the curve shown in Figure 16 indicates that beyond a given speed, the gain obtained in the increased value of OTC/N may not be sufficient to offset the increasing operational energy consumption costs for driving the rotor aerator at the increased speed. Although the latter factor was not a part of this study, it is an important consideration in system field application and demonstrates the usefulness of the prediction equation.

As the rotor aerator speed is increased, eventually liquid or slurry turbulence will occur. Under these conditions, there will be a corresponding increase in the numerical values for the Reynolds number and Froude number and there should be a more effective transfer of oxygen due to the mixing effect. The curve of Figure 16, was plotted from OTC/N calculations for speed increments of 50 rpm. Although not shown on the graph these values were computed up to 3000 rpm which was beyond the range of the Reynolds number used in the experiments. At a speed of 3000 rpm, the OTC/N value obtained was 23.4×10^{-5}.

Figure 18 shows the effect of a change in rotor diameter on the oxygen transfer coefficient per revolution of the rotor. When the rotor diameter is changed, all of the independent Pi terms are affected. As with changes in speed, both the Reynolds and Froude numbers are affected. The maximum effect on the oxygen transfer coefficient per revolution occurs when both the rotor diameter and speed are increased. The comparative calculated OTC/N values for different rotor diameters for some representative rotor aerator speeds are also shown in Figure 18.

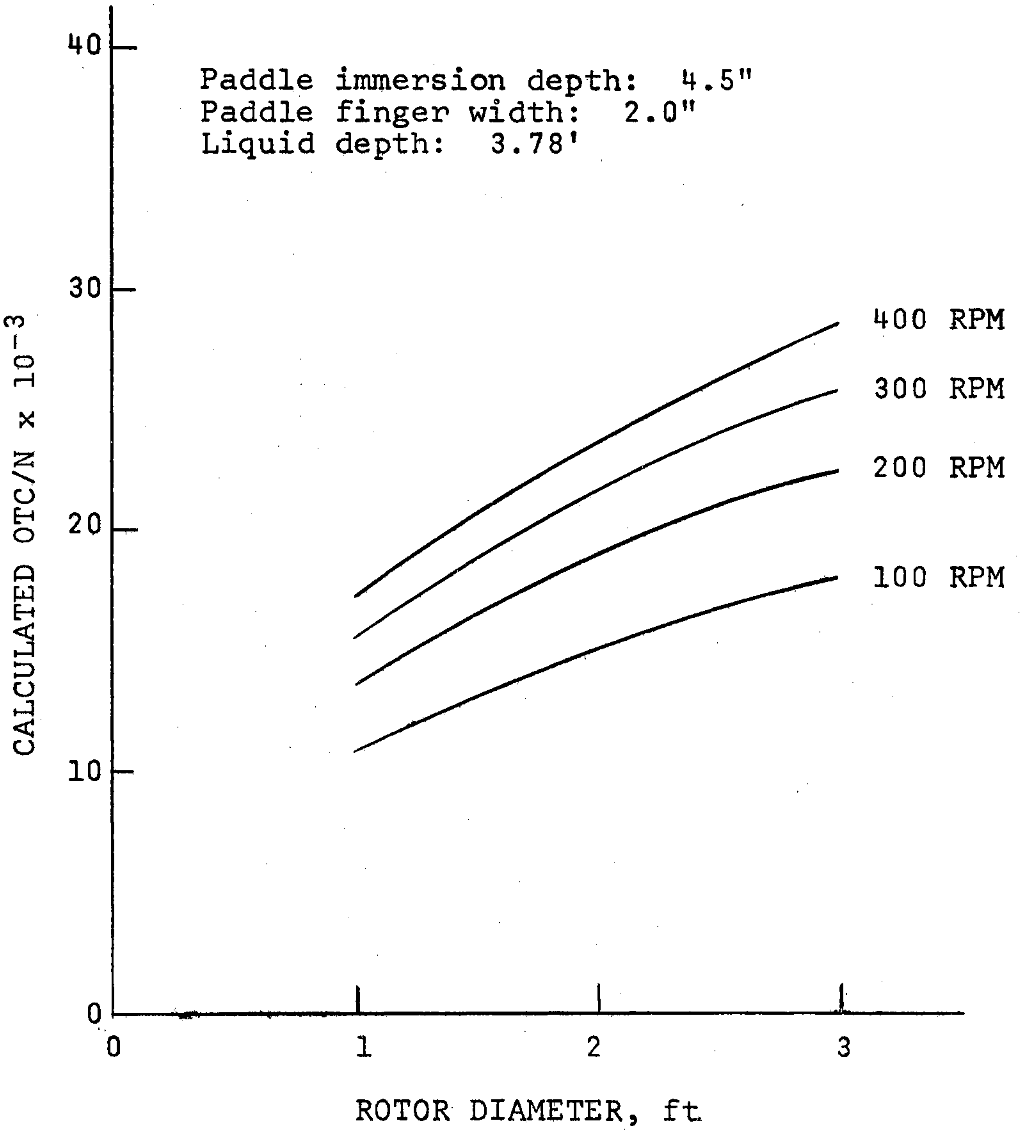


Figure 18. Effect of Speed for Varying Rotor Diameters.

Figure 19 shows the effect that a change in the ratio of the paddle finger width to the rotor diameter has on the expected oxygen transfer coefficient per revolution of the rotor. Two curves are shown:

1. A calculated data plot, Figure 19a, for an assumed prototype application.
2. The calculated data plot for the model, Figure 19b, used in the experiments.

Both curves are similar in shape as would be expected. When the Pw/D value is very low, such as for the ratios shown, there is a marked reduction in the OTC/N value for the rotor aerator.

If only the liquid or slurry depth is changed, Figure 20, the oxygen transfer coefficient per revolution of the rotor will decrease with increased depth. This would be an expected occurrence due to the increase in liquid or slurry volume if all other factors remain unchanged. By definition the oxygen transfer coefficient, OTC, represents a ratio of a unit volume of dissolved oxygen to a unit volume of the liquid or slurry for a given time period. As the liquid or slurry volume is increased and all other factors are held constant, the value of OTC will decrease. In terms of system design, if the liquid or slurry depth were already established then the selection of the diameter rotor for an application can be an important consideration. For example, in Figure 20a, if the ratio of liquid depth to rotor diameter is greater than 3, the oxygen transfer coefficient per revolution of the rotor, OTC/N, will start tending to level off. Similarly, the reverse could hold true of specifying operational liquid or slurry depths for a given diameter rotor based upon the information shown in Figure 20.

In evaluating this relationship of OTC/N to d_1/D, the volume of

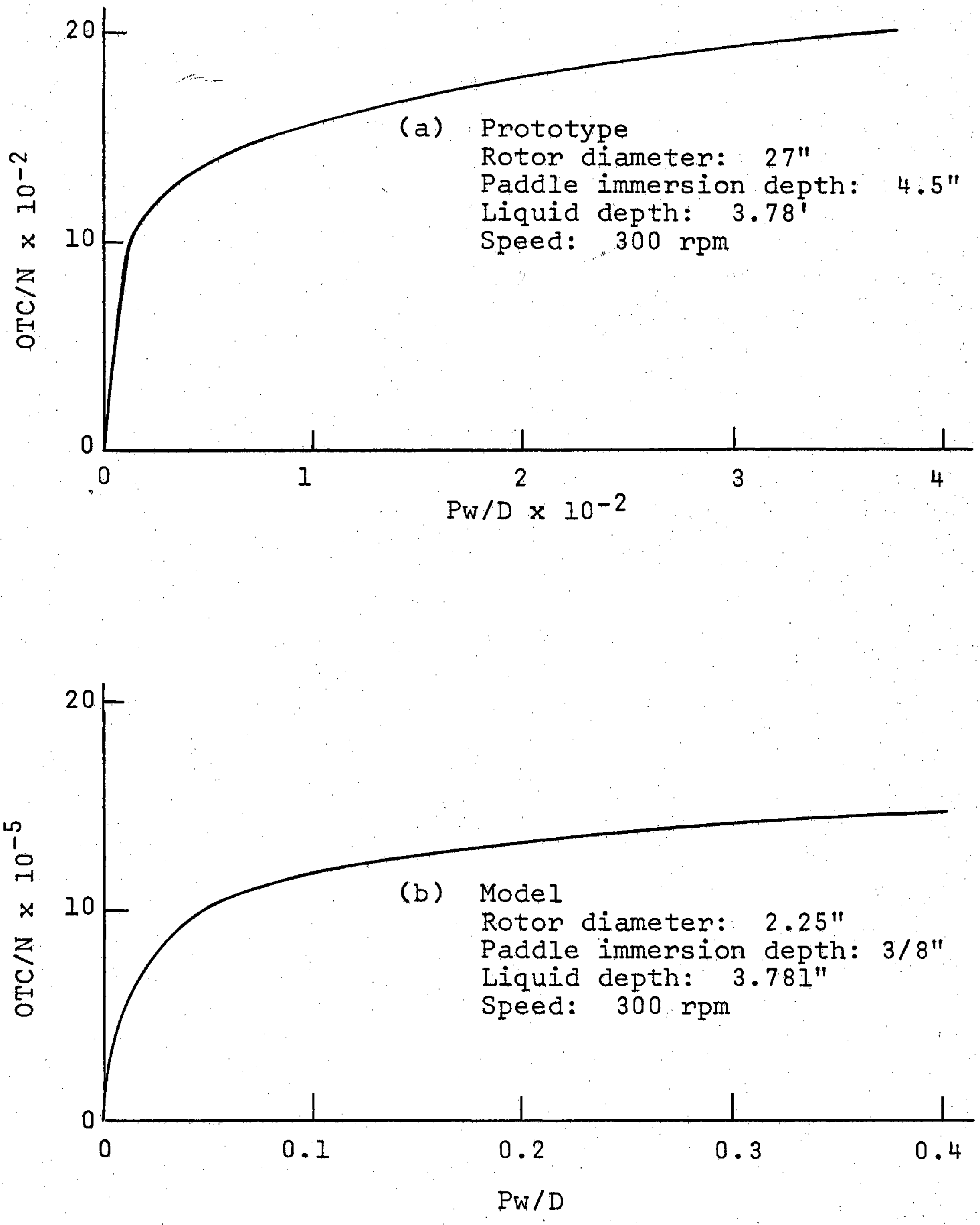


Figure 19. Predicted Performance Curves for Variation in Paddle Finger Width.

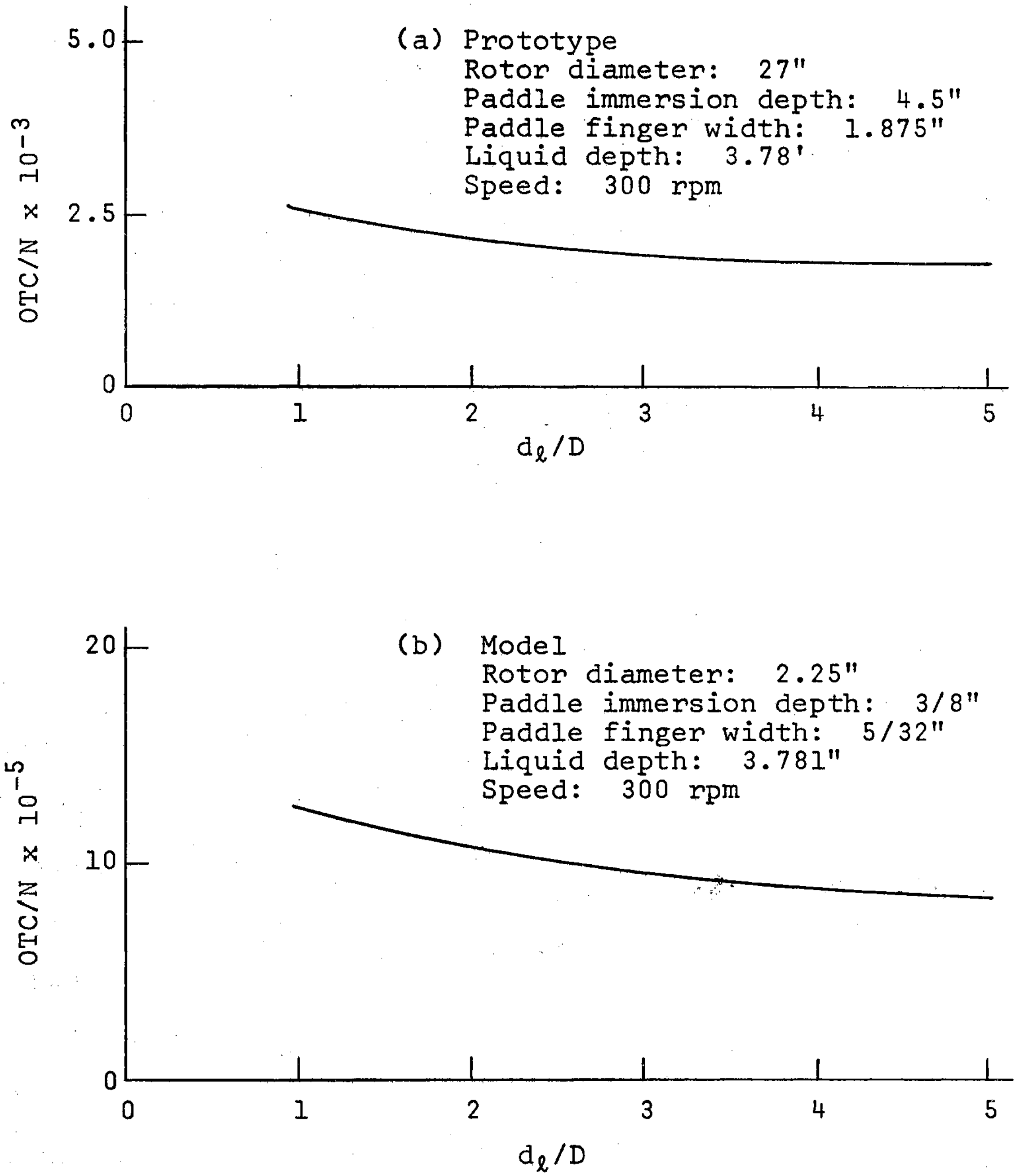


Figure 20. Predicted Performance Curves for Variation in Liquid Depth.

liquid or slurry can also be a factor. For example, if there were two different volumes of a liquid or slurry and the ratio of liquid depth to rotor aerator diameter was the same in both of these applications, the total amount of oxygen transferred, up to a certain point, would be greater for the larger liquid volume under comparable paddle aerator operating conditions.

When the paddle immersion depth is increased for a given rotor diameter, Figures 21 and 22, the oxygen transfer coefficient per revolution of the rotor is approximately a linear relationship. As the paddle finger immersion depth increases so does the paddle surface area that is in contact with the liquid. The result is an increase in the OTC/N value. With this condition an increase in power requirements can be expected as the paddle immersion depth increases for a given diameter.

Application of Prediction Equation

The prediction equation was used to estimate the probable performance of three known prototype installations. Two of these, Iowa (20) and Aberdeen, Scotland (6) involved rotor aerators being used with an oxidation ditch. Both of these studies were concerned with the evaluation of such systems. The data was reported in whole or in part and where the values were given for speed, paddle immersion depth, paddle diameter, liquid depth, and paddle finger width these were substituted into the prediction equation developed. If a value or values were missing, an assumption was necessary.

The third prototype installation evaluated was one used in brush aeration studies conducted by the Netherlands Research Institute for Public Health Engineering as reported by Pasveer (30). This study in-

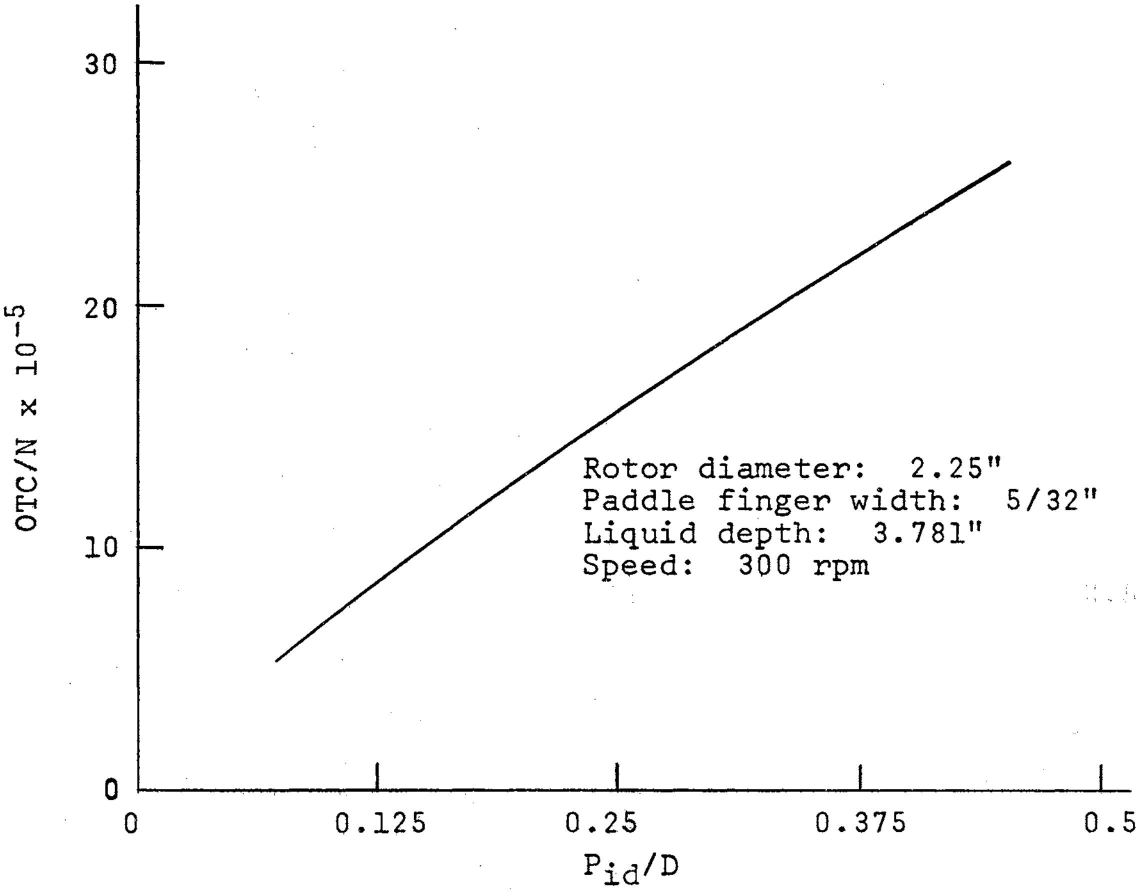


Figure 21. Predicted Performance Curve for Variation in Paddle Immersion Depth: Model Conditions.

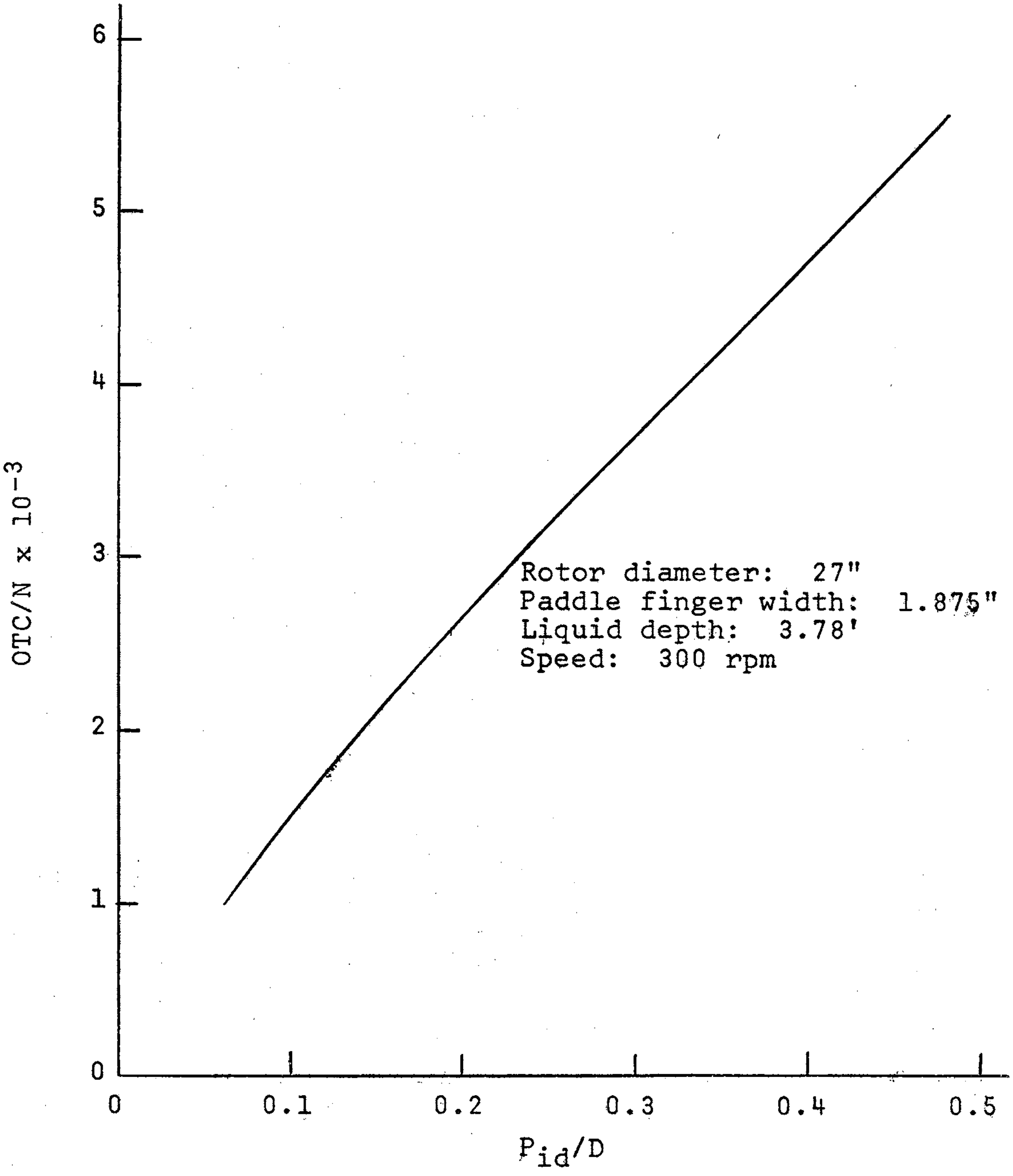


Figure 22. Predicted Performance Curve for Variation in Paddle Immersion Depth: Prototype Conditions.

volved an aeration tank having a liquid volume of 141 cubic feet. An angle type blade was used in contrast to the flat, rectangular shaped blade of this study. It was necessary to make two assumptions:

1. Liquid depth.
2. Paddle finger width.

The depth of the liquid or slurry was taken as being 3 to 5 feet this being the range that might be found in an oxidation ditch. The prediction equation evaluation included an evaluation for both liquid depth conditions. The angle-iron aerator finger width was not known so the width of the paddle finger studied was used.

The OTC value obtained from the prediction equation was related to the expression developed earlier:

$$\mathrm{OTC} = -\frac{\ln\left[\frac{1-C_2/C_s}{1-C_1/C_s}\right]}{\Delta t}$$

As most of the prototype rotor aerator speeds were reported in units of rpm, the dimension used for OTC was 1/min. The initial time period, t, selected for system performance evaluation was sixty minutes. This served as the basis for estimating the per cent change in dissolved oxygen that might take place in a liquid over a one hour period. The procedure followed can be visualized further by referring to Figures 13 and 14 which illustrate the experiment data plot on semi-log paper. It is based upon the premise that there is no dissolved oxygen present in the liquid initially and the OTC value is the criterion for measuring the effectiveness of the rotor aerator for oxygen transfer.

The predicted amount of oxygen transfer, POT, from air to a liquid or slurry was determined from the following expression:

$$POT = 60(10^{OTC})\ c_s = mg/l(hr)$$

where:

$60(10^{OTC})$ is the per cent change in dissolved oxygen concentration for a one hour time period,1/hr.

c_s = dissolved oxygen concentration level in water at liquid saturation for the known or assumed temperature, mg/l.

The units for POT, mg/l (hr), are approximately equal to oz/hr (1000 ft^3). When POT was multiplied times the known or estimated volume of liquid or slurry being aerated, this gave the total amount of oxygen transferred by a mechanical aerator, or what can be referred to as the oxygenation capacity for a given system. Examples of prediction equation application follow.

At Aberdeen, Scotland (6), a study was made of a method of handling livestock wastes on a limited acreage. It involved the use of a primary oxidation ditch for treatment of swine waste. The rotor used for the experiment was 18" in diameter and consisted of 4 arms each having six $4\frac{1}{2}$" x $6\frac{1}{2}$" cup shaped blades. A photograph of the primary rotor aerator included with this report indicated that the $4\frac{1}{2}$" dimension was the equivalent of the paddle finger width, P_w, for use in the prediction equation. The speed for rotor operation was at approximately 80 rpm and the paddle blade was immersed into the slurry at a depth of 2" - $2\frac{1}{2}$". The slurry depth was not given but the overall ditch volume figure was. This was approximately 200 cubic feet. The oxygenation capacity of the Aberdeen rotor aerator was measured as 2.14 lb/day.

In applying the prediction equation to the Aberdeen, Scotland installation, the values used for density, ρ, and liquid absolute viscosity, μ, in Reynolds number were that of water. Where swine wastes were being treated in the system, it would not be expected that these values be the same. An estimated volume of 200 cubic feet was given for ditch capacity. The basic surface area dimensions for the oxidation ditch were given but not the slurry depth. From these figures, the slurry depth was computed and this value substituted for d_1 in the prediction equation. This was found to be 0.56' or 6.72". Calculations of OTC were made for both a 2" and $2\frac{1}{2}$" paddle immersion depth. In addition, calculations were made for a slurry depth of 6", 12" and 1.5". With each of these calculations, the new slurry volume was determined. These results are summarized in Table VI.

TABLE VI

APPLICATION OF PREDICTION EQUATION TO ABERDEEN, SCOTLAND (6) DATA

d, Slurry Depth inches	Approx. Ditch Volume cu.ft.	Pid, Paddle Immersion Depth, inches	Pw, Paddle Finger Width inches	OTC Anti-logarithm 1/min.	Oxygenation* Capacity lb/day
6	184	2.0	4.5	1.26	2.09
6	184	2.5	4.5	1.32	2.19
6.5	200**	2.0	4.5	1.25	2.26
6.5	200**	2.5	4.5	1.31	2.37
12	367	2.0	4.5	1.21	4.00
12	367	2.5	4.5	1.26	4.17
18	550	2.0	4.5	1.18	5.88
18	550	2.5	4.5	1.23	6.09

* Value obtained for prediction equation developed.

** For this condition, the measured oxygenation capacity reported was 2.14 lb/day.

The figures of Table VI are based upon 24 hour operation of the rotor aerator. In the Aberdeen, Scotland experiments, the rotor aerator was time clock controlled but the operational cycle was not given. It was assumed that the only time the rotor aerator was inoperative was the period for effluent settling in the primary oxidation ditch just prior to its discharge. The Aberdeen, Scotland report discussion pointed out that an oxygen deficit was observed in the experiments. The measured oxygenation capacity for this installation was 2.14 lb/day and this measurement was not possible until near completion of the experiments. For the number of hogs housed, the estimated oxygen need was 10.8 lb/day. The latter statement is significant in that it shows the merit of the use of a prediction equation. The figures of Table VI, besides showing a similar estimated oxygenation capacity to the results reported, also suggest that the system as described was inadequate for the performance desired. This is of value to the design or application engineer as it provides a useful tool for making a preliminary evaluation of design recommendation prior to field installation. In this case, parameters could be selected and evaluated until the desired combination were obtained.

The Iowa State University study reported by Knight (20) involved the evaluation of the performance of a mechanical aerator operating in a full-sized oxidation ditch. The rotor dimensions were:

Length: 3 ft. Diameter: $27\frac{1}{2}$" Paddle finger width: 2"

A variable speed motor drive was used to provide an output speed range of 175 to 350 rpm. This speed was further reduced by means of a chain and sprocket drive to give a theoretical rotor aerator speed range of 54.4 to 108.8 rpm. The oxygen uptake experiments were made with water which was deoxygenated by using sodium sulfite with a cobalt chloride catalyst.

The Iowa study did not attempt to establish a dimensionless oxygen transfer coefficient, OTC, such as was done in this dissertation. Instead, a reaeration constant, K_d, was used the expression of which was

$$\frac{\ln D_1 - \ln D_2}{t_2 - t_1}$$

where:

D_1, D_2 were the dissolved oxygen deficits at 20°C, 760mm pressure, and zero dissolved oxygen in the water, in mg/l, at times t_1 and t_2 respectively.

The comparable expression in this dissertation for $\frac{\ln D_1 - \ln D_2}{t_2 - t_1}$ is $\frac{\ln \frac{C_s - C_t}{C_s - C_i}}{\Delta t}$ x 100 as shown in Figures 13 and 14.

The prediction equation developed was evaluated for the data and results of calculations from a typical run described by Knight. This test run was for a paddle immersion depth of 3 inches and an oxidation ditch water volume of 7,260 cubic feet. From the oxidation ditch plan view and cross section given, the liquid depth was calculated to be 4.5 feet. Prediction equation evaluations were then made for the 3, 4, and 5 foot liquid depths and the 4.5 foot condition.

In making the comparative evaluation of the prediction equation to the Iowa data, the initial concentration level of oxygen in the liquid, C_i, was taken as zero for time, t_1. This was done because the prediction equation had been developed in this manner and for simplification in evaluation. This meant that the corresponding value for the Iowa study would have been 9.21 mg/l for dissolved oxygen deficit at time, t_1, if a zero condition had been obtained. The concentration level of oxygen in the liquid, C_2, at time, t_2, was 6.33 mg/l which represented a one hour period.

Using the prediction equation, the oxygen transfer coefficients were found to be 1.32, 1.29, 1.28 and 1.27 respectively for the mechanical aerator operating conditions previously described. These values were for corresponding liquid slurry depths of 3, 4, 4.5 and 5.0 feet. The percentage of the overall dissolved oxygen saturation concentration levels for these conditions after an hour period were calculated to be 79, 77.5, 76.9, and 76.3 per cent. This was equivalent to a concentration of 7.27, 7.14, 7.08, and 7.02 mg/l of dissolved oxygen in the liquid, C_2, as compared to the 6.33 mg/l value measured in the Iowa study. This again demonstrated a good relationship between the prediction equation developed and field application.

For the solution of gases in liquids in motion Pasveer (29)(30) stated that the oxygenation capacity of an aeration unit was equal to $\frac{dc}{dt}$, a time rate of change in the concentration of the dissolved oxygen in a liquid. He derived the expression $\frac{dc}{dt} = 25.9 \tan\alpha \sqrt{\frac{K_{10}}{K_t}}$ for oxygenation capacity where:

$$\tan\alpha \text{ represented } \frac{1}{t_1 - t_o} \log \frac{C_{Ls} - C_o}{C_{Ls} - C_1}$$

and:

$\sqrt{\frac{K_{10}}{K_t}}$ represented a variation in temperature as compared to $10^\circ C$.

The terms C_{Ls}, C_o, and C_1 represent dissolved oxygen concentration levels in a liquid at saturation, initially, e.g. time, t_o, and at any time, t_1. For a time period of hours and a degree of concentration of oxygen in grams per cubic meter, the units for oxygenation capacity were grams per hour per cubic meter which is the equivalent of ounces per hour per 1000 cu. ft.

The expression $\frac{1}{t_1 - t_o} \log \frac{C_{Ls} - C_o}{C_{Ls} - C_1}$ used by Pasveer is comparable to the expression developed for OTC, the oxygen transfer coefficient, except for the arrangement of the dissolved oxygen concentration levels in the numerator. A computational check for tanα and OTC using the dissolved oxygen concentration levels reported by Pasveer gave similar results. Based upon this evaluation, the prediction equation was then used to compute an estimated OTC for substitution into the Pasveer expression for oxygenation capacity. These results obtained are compared graphically in Figure 23.

In Figure 23, the solid line represents a plot of the data obtained in the Netherlands study while the dashed line represents the predicted values. For reason of graphical clarity, the prediction equation calculations for the 3 foot and 5 foot liquid depth were averaged and this point plotted. The prediction equation values for the 5 foot liquid depth were slightly less than that for the 3 foot depth. This would be as expected due to the increased volume of liquid being aerated while all other system conditions remained constant. The predicted rotor aerator oxygenation capacity for the 7 to 12 cm paddle immersion depth is essentially in agreement with the Netherlands performance data reported. There is a more notable difference between the actual value and the predicted value at the 5 cm and 14 cm paddle immersion depth. Part of this difference could be reflected by the paddle blade configuration used in field application and that used for prediction equation development. The relationship of liquid depth to the liquid volume could have been

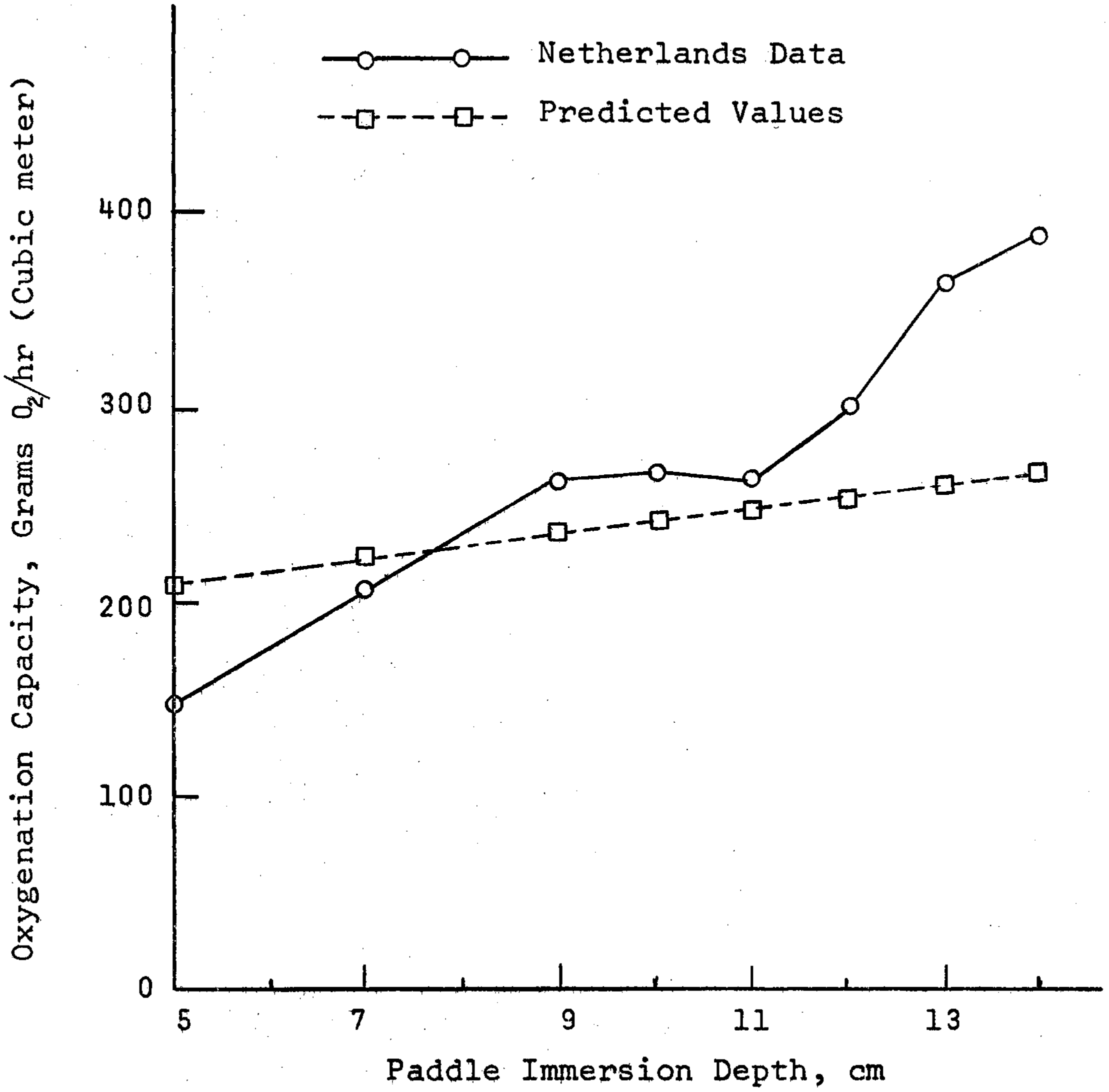


Figure 23. Comparison of Prediction Equation Values to Data Reported by Pasveer (30). Rotor Aerator Speed 114 RPM; Paddle Diameter 16.5"

another contributing factor. Although the liquid volume was given, the tank surface area and liquid depth dimensions were not indicated.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Summary

An experimental investigation involving the principles of dimensional analysis and similitude was conducted to evaluate the effectiveness of oxygen transfer from air to liquid by rotor or "paddle wheel" aerators. The physical pertinent quantities believed important in paddle aerator system operation were identified, Table I. Using the Buckingham Pi theorem, these Pi terms were then combined into dimensionless ratios, p.24.

Of the dimensionless ratios formed, Pi_1, OTC/N, the oxygen transfer coefficient per revolution of rotor, was selected as the dependent variable and represented the physical response being measured in the experiments conducted. The remaining Pi terms were treated as independent variables.

The experiments were done with physically similar models using distilled water as the liquid according to the experiment schedule presented in Table III for model aerator speeds based upon the variation made in the Froude number. The selected prototype speed range from which the model paddle aerator speed computations were made was from 60 to 300 rpm.

Data was collected varying one independent Pi term at a time. The method of least squares was used in the development of the component equations which related the dependent Pi term, OTC/N, to each of the independent Pi terms. The component equations were combined by multiplication to obtain the prediction equation, p. 54. A series of paddle aerator performance curves were prepared from the prediction equation evaluating the effects of paddle speed, paddle diameter, paddle immersion depth, paddle finger width, and liquid depth.

Using the prediction equation, a comparison was made between the predicted values and the observed values. The regression line yielded a slope of 1.44 and a correlation coefficient of 0.917. The prediction equation was also evaluated against data obtained from three prototype installations.

The results obtained identify the factors pertinent to oxygen transfer by paddle wheel aerators and show how these factors can be applied to paddle aerator system design.

Conclusions

The laboratory method developed presents a technique not heretofore considered for use in the engineering design and analysis of a paddle aerator system. This procedure can be used to obtain quantitative prediction equations for estimating the performance of mechanical aerator systems. Once a prediction equation for a given system is developed, it can then be further used to evaluate new applications provided the parameters involved fall within the range of the prediction equation developed.

The oxygen transfer coefficient per revolution of rotor can be defined by a prediction equation.

$$\frac{OTC}{N} = (7.42 \times 10^{-7}) \left[Re^{(0.700)} \times Fr^{(-0.187)} \times \left(\frac{Pid}{D}\right)^{0.856} \times \left(\frac{Pw}{D}\right)^{0.183} \times \left(\frac{d_1}{D}\right)^{-0.275}\right]$$

This equation takes into consideration the characteristics of the liquid or slurry being aerated, paddle speed, paddle diameter, paddle immersion depth, paddle finger width, and the liquid or slurry depth.

The prediction equation developed can be used to estimate prototype rotor aerator performance. This validation was shown by analysis of data obtained from prototype rotor aerator system installations located in Scotland and Iowa. In Scotland, the measured oxygenation capacity was reported as 2.14 lb/day. Using the prediction equation, the calculated oxygenation capacity was 2.26 and 2.37 lb/day for the parameters selected. For the Iowa study, the predicted dissolved oxygen concentration levels ranged from 7.02 to 7.27 mg/l as compared to a measured value of 6.33 mg/l. However, for the studies reported by Pasveer, there was both good agreement and some disagreement in the prediction equation validation. The disagreement occurred in the region of the 5 cm and 13 cm paddle immersion depths. This could be due in part to the differences between the model and prototype as described earlier and the manner in which the OTC slope determination was made.

Based upon the range of the experiments conducted and the analysis used, the following statements can be made for the oxygen transfer coefficient per revolution of rotor, OTC/N.

1. An increase in the diameter or speed of the paddle aerator will result in an increase in OTC/N.
2. As paddle immersion depth is increased, OTC/N increases. This relationship is approximately linear.
3. OTC/N decreases with an increase in liquid or slurry depth.
4. The ratio of paddle finger width to paddle diameter has a well-defined effect on OTC/N when the ratio of $\frac{Pw}{D}$ is less than 0.1.

Suggestions for Further Study

1. The following type experiments are suggested:
    a. Paddle configuration

       Concave or convex shaped fingers might be used in lieu of flat, rectangular shaped fingers.
    b. Change aerator tank dimensions, e.g. tank length and width.
2. Validate the prediction equation developed using a full-size prototype.
3. Evaluate the prediction equation for different type materials, in particular animal wastes.
4. Develop a prediction equation for an oxidation ditch.

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APPENDIX A

EXPERIMENT TEST SEQUENCE

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EXPERIMENT SEQUENCE

Test No.	Pi term varied	Speed, N RPM	Paddle depth, Pid inches	Rotor diameter, D inches	Liquid depth, D inches	Paddle finger width, Pw inches
1	Model *	300	3/8	2.25	3 25/32	5/32
2**	Pi_8 **	300	3/8	2.25	4 25/32	5/32
3	Pi_8	300	3/8	2.25	5 25/32	5/32
4	Pi_3	218	45/64	4.25	7 3/32	0.294
5	Pi_3	218	45/64	4.25	7 3/32	0.294
6	Pi_4	83.6	45/64	4.25	7 9/64	0.294
7	Pi_3	230	45/64	4.25	7 9/64	0.294
8	Pi_3	249	35/64	3.25	6 17/32	0.225
9	Pi_4	143	35/64	3.25	6 17/32	0.225
10	Pi_3	249	35/64	3.25	6 17/32	0.225
11	Pi_6	300	5/8	2.25	3 25/32	5/32
12	Pi_6	300	1/8	2.25	3 25/32	5/32
13	Model *	300	3/8	2.25	3 25/32	5/32
14	Pi_8	300	3/8	2.25	4 25/32	5/32
15	Pi_8	300	3/8	2.25	5 25/32	5/32
16	Pi_8	300	3/8	2.25	5 25/32	5/32
17	Pi_8	300	3/8	2.25	5 9/32	5/32
18	Pi_8	300	3/8	2.25	5 9/32	5/32
19	Pi_8	300	3/8	2.25	5 9/32	5/32
20	Pi_7	300	3/8	2.25	3 25/32	1/2
21	Pi_7	300	3/8	2.25	3 25/32	1/2
22	Pi_7	300	3/8	2.25	3 25/32	1/2
23	Pi_7	300	3/8	2.25	3 25/32	1/2
24	Pi_7	300	3/8	2.25	3 25/32	1/2
25	Pi_7	300	3/8	2.25	3 25/32	1/4
26	Pi_7	300	3/8	2.25	3 25/32	1/4
27	Pi_7	300	3/8	2.25	3 25/32	1/4
28	Model *	300	3/8	2.25	3 25/32	5/32
29	Model *	300	3/8	2.25	3 25/32	5/32
30	Pi_3	420	13/64	1.25	1 61/64	0.086
31	Pi_3	410	13/64	1.25	1 61/64	0.086
32	Pi_3	402	13/64	1.25	1 61/64	0.086
33	Pi_4	966	13/64	1.25	1 61/64	0.086
34	Pi_4	966	13/64	1.25	1 61/64	0.086
35	Pi_4	966	13/64	1.25	1 61/64	0.086

Model *: The rotor aerator physical dimensions when the prototype is scaled to a 1:12 ratio and speed calculation is based upon Froude number.

** Test No. 2 results were dropped due to an error in experiment set-up.

$Pi_3 = \frac{Ne\rho ND^2}{\mu}$ $Pi_4 = \frac{NeDN^2}{G}$ $Pi_6 = \frac{Pid}{D}$ $Pi_7 = \frac{Pw}{D}$ $Pi_8 = \frac{d_{\ell}}{D}$

APPENDIX B

EXPERIMENT DATA OTC VALUES and CORRELATION COEFFICIENTS

APPENDIX B

EXPERIMENT DATA CORRELATION COEFFICIENTS AND OTC VALUES

Pi Term	Experiment Number	OTC, $\frac{1}{t}$	Correlation Coefficient, R
Reynolds Number, Pi$_3$			
	4	-0.0985	0.643
	5	-0.0457	0.702
	7	-0.0954	0.600
	8	-0.0461	0.751
	10	-0.0471	0.681
	30	-0.0301	0.788
	31	-0.0349	0.703
	32	-0.0452	0.711
Froude Number, Pi$_4$			
	6	-0.0137	0.779
	9	-0.0201	0.726
	33	-0.0827	0.687
	34	-0.0688	0.675
	35	-0.0890	0.668
Paddle Immersion Depth/ Rotor Diameter, Pi$_6$			
	11	-0.0453	0.715
	12	-0.0109	0.855
	1	-0.0283	-0.989
	13	-0.0306	0.723
	28	-0.0269	0.764
	29	-0.0197	0.786
Paddle Finger Width/ Rotor Diameter, Pi$_7$			
	20	-0.0356	0.738
	21	-0.0321	0.704
	22	-0.0183	0.769
	23	-0.0474	0.767
	24	-0.0357	0.756
	25	-0.0281	0.755
	26	-0.0296	0.761
	27	-0.0302	0.768
	1	-0.0283	-0.989
	13	-0.0306	0.723
	28	-0.0269	0.764
	29	-0.0197	0.786

APPENDIX B (Continued)

EXPERIMENT DATA CORRELATION COEFFICIENTS AND OTC VALUES

Pi Term	Experiment Number	OTC, $\frac{1}{t}$	Correlation Coefficient, R
Liquid Depth/Rotor Diameter, Pi_8			
	3	-0.0226	0.732
	14	-0.0312	0.766
	15	-0.0288	0.717
	16	-0.0174	0.736
	17	-0.0210	0.838
	18	-0.0293	0.765
	19	-0.0254	0.771
	1	-0.0283	-0.989
	13	-0.0306	0.723
	28	-0.0269	0.764
	29	-0.0197	0.786

VITA

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